Digital Twins in Immersive Healthcare: A Systematic Review of Metaverse Technologies in Clinical Training and Patient Care and a Cost-Benefit Analysis

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Abstract

Digital twins combined with immersive technologies (VR, AR, XR) are transforming healthcare delivery, clinical training, and patient monitoring. This study systematically assesses whether digital twin-enhanced immersive systems improve clinical outcomes, training effectiveness, and decision-making compared to conventional methods. A PRISMA-guided systematic review was conducted across PubMed and Scopus (2015–2025), screening 31 eligible articles. Bibliometric and thematic analyses were employed for categorization. Included studies report benefits in surgical planning, diagnostic support and rehabilitation, delivering greater precision and user engagement. Gaps remain in large-scale clinical validation, consistent rehab efficacy and system-level scalability. A cost–benefit appraisal of two macro-areas—*Patient-Specific Virtual Care* and *Hospital Simulation Networks*—confirms strong economic viability. Key value drivers are the avoidance of invasive procedures (e.g. roughly 675 000 per year saved by CT-derived fractional-flow-reserve workflows) and operational gains (e.g. average 12-minute reductions in operating-room time per major case).

Keywords: digital twin; healthcare; medicine; health system; augmented reality; metaverse; immersive reality

1 Introduction

Digital twins (DT) and immersive technologies such as virtual reality (VR), augmented reality (AR), and extended reality (XR) are beginning to change how healthcare is delivered, taught, and experienced Wang et al. (2024). Originally used mainly in fields like aerospace or manufacturing, digital twins are now being explored in medicine as tools to improve training, treatment, and patient monitoring. These virtual models, which mirror physical systems in real time, when combined with immersive technologies and integrated into the broader concept of the metaverse, offer new ways to interact with clinical environments and data in highly realistic settings Bracq et al. (2019).

Healthcare professionals, students, and patients are increasingly engaging with these technologies across a wide range of use cases. Examples include operating room planning through VR reconstructions, surgical training on 3D patient models, remote rehabilitation such as kinesitherapy, and digital diagnostics. Digital twins and the metaverse have the potential to make fields and processes such as medical education, treatments, and health monitoring more interactive, accessible, and precise compared to traditional tools Bruynseels et al. (2018).

While these technologies are promising, it is essential to systematically evaluate whether digital twin- and metaverse-based systems truly offer measurable benefits over conventional methods. Traditional approaches, such as non-immersive simulations, textbook-based anatomy learning, or in-person physical therapy, have long represented the gold standard in clinical training and care.

An important dimension in assessing the adoption of these advanced technologies is the cost-benefit analysis, which evaluates not only the clinical effectiveness but also the economic impact.

Cost-benefit studies consider factors such as the initial investment in hardware and software, maintenance expenses, training costs, and potential savings from improved patient outcomes, reduced errors, and shorter hospital stays McIntosh et al. (2006a). Early evidence suggests that while immersive systems and digital twins may require significant upfront costs, their ability to enhance training efficiency, reduce procedural complications, and enable remote monitoring can lead to substantial long-term savings and improved resource allocation Moro et al. (2017); Pottle (2019). Therefore, a rigorous cost-benefit evaluation is crucial to justify the integration of these technologies into healthcare workflows and to guide policy and investment decisions.

2 Study Objectives

The project is structured around two key objectives: The first aim is is to conduct a systematic review of studies on real-world implementations of digital twin technologies integrated with immersive environments—specifically VR, AR, XR, or metaverse platforms—in healthcare and clinical education. The review focuses on original research involving human participants (patients, students, professionals) and reporting measurable outcomes in clinical efficacy, training performance, usability, or implementation feasibility.

The central research question is:

Do immersive systems integrated with digital twins (VR, AR, XR) improve clinical outcomes, training effectiveness, and decision-making compared to traditional methods?

Using PRISMA guidelines, Moher et al. (2009), the review extracts thematic clusters to clarify the practical utility and future potential of these technologies, ultimately identifying high-impact use cases for economic evaluation. Building on the evidence from the review, the second objective is to conduct a cost-benefit analysis (CBA) of immersive digital twin implementations in real healthcare settings. The analysis compares three scenarios over a 15-year time horizon: A current status quo using traditional 2D imaging and manual planning, a partial digital twin adoption without immersive interfaces and a full deployment of XR-enabled digital twins at departmental or regional scale. The baseline reference is a tertiary Italian hospital with 600 acute beds and approximately 60,000 annual CT/MRI exams—consistent with institutions like ASST Grande Ospedale Metropolitano Niguarda (2023) in Milan (approximately 1,200 total beds, 600–700 acute).

3 Systematic Review

3.1 Materials and methods

This review was conducted in line with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and methodological rigor. To identify relevant literature on the integration of digital twin technologies with immersive platforms in healthcare, we designed a two-stage search strategy across multiple databases.

Our primary search was conducted in PubMed [1] using a predefined Boolean query. To maximize coverage, we replicated and optimized this search for Scopus Elsevier (2023), adapting the syntax to accommodate database-specific operators. All retrieved records were exported to a reference management software (EndNote) [2] and deduplicated.

3.2 Search Strategy

In the first stage, we applied the following broad query to capture a comprehensive set of studies on digital twins in healthcare contexts: *("digital twin" OR "digital twins") AND ("healthcare"*

[1] https://pubmed.ncbi.nlm.nih.gov/
[2] https://endnote.com/

OR "medicine" OR "clinical" OR "hospital" OR "patient monitoring" OR "health system") AND ("performance" OR "evaluation" OR "implementation" OR "validation" OR "development" OR "simulation" OR "feasibility")
Date of the query: 19/05/2025

This initial search gave 527 results. A Bag of Words (BoW) representation based on the corpus of 527 scientific abstracts retrieved from PubMed is shown in Figure B1 in the Appendix B. These records were selected using a focused query designed to capture the literature on Digital Twins in medical contexts, with particular emphasis on implementation and performance-related aspects, as previously outlined. The results were filtered to include only publications from the last five years. The data retrieval process was carried out using the RISmed package (v2.1.7) Kovalchik (2017) in R (v4.3.1) R R Core Team (2023), which enabled programmatic access to PubMed through the E-utilities API Kovalchik (2019). For each article, metadata including PubMed ID, title, publication year, journal, and abstract was extracted and stored for further analysis.

The data preprocessing workflow, implemented in Orange Data Mining (v3.35.0), an open-source visual analytics platform [3], is shown in Figure B2 of the Appendix B. The pipeline included standard natural language processing steps. The resulting BoW visualization reveals two primary thematic domains in the literature: a clinical-performance axis, and a technological-development axis. This dual structure illustrates the evolving landscape of Digital Twin applications in medicine. Although much of the existing research remains grounded in clinical evaluation and system performance, our systematic review is specifically oriented toward the integration of Virtual and Augmented Reality technologies within Digital Twin frameworks.

In addition, the bibliometric analysis included a relational semantic analysis using the bibliometrix R package (v4.1.2) for network mapping Aria and Cuccurullo (2017)

To further explore our analysis, the co-occurrence network Figure 1 was constructed and thematic clusters were identified via the Louvain community detection algorithm Blondel et al. (2008). The network modularity score (Q = 0.42) indicates a clear community structure. In fact, the network analysis revealed four distinct research clusters: Computational Biomechanics (Purple), Translational Medicine(Red), Diagnostic Validation (Blue), Clinical Implementation (Green)

To narrow the corpus to works involving immersive technologies, we refined our search strategy to include metaverse and extended reality terminologies. This refinement proved particularly crucial given the field's explosive growth (see Table 1). The modified Boolean query incorporated is the following:

("digital twin" OR "digital twins" OR "digital-twin" OR "digital-twins") AND ("healthcare" OR "medicine" OR "clinical" OR "hospital" OR "therapeutic planning" OR "patient monitoring" OR "therapy" OR "health system" OR "health") AND ("performance" OR "evaluation" OR "implementation" OR "validation" OR "development" OR "simulation" OR "feasibility" OR "optimization" OR "outcome" OR "efficacy") AND ("metaverse" OR "VR" OR "XR" OR "AR" OR "VR/AR" OR "Augmented Reality" OR "AR/VR" OR "Virtual Reality" OR "Extended Reality" OR "Computer Vision" OR "4D" OR "4-D")
Date of the query: 19/05/2025

We restricted results to studies published within the last 10 years (2015-2025) to ensure relevance to current technological capabilities and healthcare practices. This refined search resulted in 55 studies. After confirming there were no duplicates, we exported the citations to a CSV file and uploaded them into Rayyan, a collaborative web-based platform for systematic reviews Ouzzani et al. (2016). Rayyan facilitated abstract screening by allowing reviewers to independently assess and tag studies.

[3] https://orange.biolab.si/

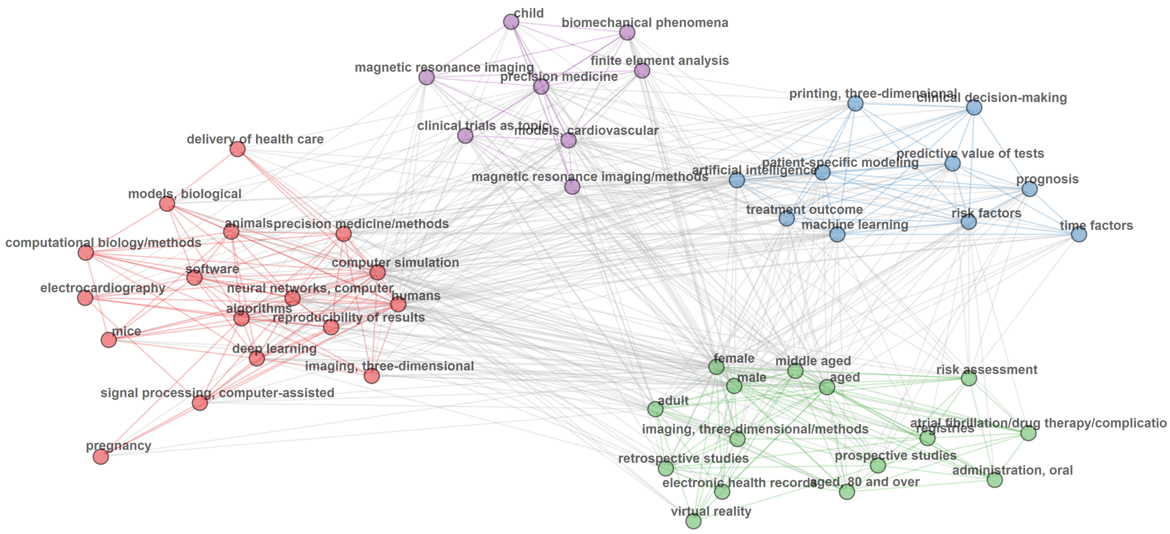

Figure 1: Co-occurrence network (Louvain clustering, Q=0.42)

Table 1: AR/VR Publication Trends (2019-2025)

Period	Publications (n)	Growth (%)	Cumulative
2019-2022	42	–	42
2023-2025	185	+341	227

3.3 Screening and Eligibility

Two reviewers independently screened the abstracts for relevance, while a third reviewer served as an adjudicator in cases of disagreement. The inclusion and exclusion criteria were developed in alignment with the PICO framework (Richardson et al. (1995)), which structured our research question as follows: In medical professionals, students, or patients (Population), does the use of digital twin-enhanced metaverse technologies (Intervention), compared to conventional methods (Comparator), improve clinical training, health monitoring, diagnosis, or treatment outcomes (Outcomes)?

3.4 Inclusion Criteria

This review includes studies involving human participants in healthcare or clinical training settings, such as patients, students, or healthcare professionals. Eligible studies must implement digital twin technologies integrated with immersive technologies including virtual reality (VR), augmented reality (AR), extended reality (XR), or metaverse platforms. Applications may cover areas like simulation, monitoring, clinical training, virtual environments, or digital anatomical modeling. Moreover, studies are required to report measurable outcomes—such as training efficiency, learning retention, diagnostic or therapeutic accuracy, user engagement, or system feasibility. Only original research will be considered, including pilot or case studies, feasibility or validation work, clinical trials, and technical evaluations specifically conducted in healthcare or educational contexts. The review is restricted to works written in English and preferably published within the last ten years, i.e., from 2015 onward.

3.5 Exclusion Criteria

Studies were be excluded if they didn't involve human subjects or participants relevant to the healthcare or clinical training domains. Research focusing solely on engineering or industrial applications, without a clear link to healthcare, were not be considered. Additionally, papers in which digital twin technologies and immersive environments like VR or XR were used independently, without integration, were excluded. The review also disregard studies that present only theoretical frameworks without any practical implementation or without assessment of clinical, educational, or technological outcomes. Finally, review articles, meta-analyses, editorials, white papers, and non–peer-reviewed literature are not eligible for inclusion.

The same inclusion and exclusion criteria were applied during the full-text screening phase. Ultimately, 31 studies met all eligibility requirements and were included in the final analysis. The inclusion and exclusion criteria were defined in accordance with established guidelines for systematic reviews (Higgins et al., 2024)

3.6 PRISMA Flow Diagram

The selection process was conducted in two phases in accordance with the PRISMA guidelines. The complete flow diagram is shown in Figure B3 of the Appendix B, and detailed study characteristics are provided in Appendix A. In the first phase, 55 records were screened based on their titles and abstracts. Of these, 22 were excluded for the following reasons: **Non-healthcare applications (n=10):** Studies focused on digital twin applications in non-healthcare domains, such as industrial engineering or robotics and **Lack of digital twin and VR integration (n=12):** Articles that either employed virtual reality (VR) environments solely for behavioral and described digital twin systems without immersive or interactive components.

33 records advanced to full-text assessment, but 2 studies were excluded since they did not meet the criteria previously outlined

4 Relevant Papers

Following the systematic selection process, 31 studies met our inclusion criteria for digital twin and VR integration in healthcare. The analysis revealed both transformative applications and persistent challenges across clinical domains. Studies as Lee et al. (2025) and Kleinbeck et al. (2024) demonstrate VR-based digital twins reduce pediatric preoperative anxiety and enhance surgical planning, while Shu et al. (2023) achieves sub-1.4mm accuracy in skull base surgery simulations. Chakshu et al. (2021) confirms non-invasive cardiac diagnostics match invasive FFR measurements, Zheng et al. (2025) reports superior usability of VR over 3D desktop software for thoracic planning. and Palumbo et al. (2022) adds promise with sub-3mm AR catheter navigation, However, Xu et al. (2024) notes limited functional recovery in stroke rehabilitation, Kwak et al. (2024) finds VR audiometry no better than conventional methods,Laaki et al. (2019) reveals 5% of users experience VR-induced discomfort and Tsekleves et al. (2014) highlights scalability challenges in low-cost VR rehab. Together, these studies showcase transformative potential in precision medicine but underscore needs for clinical validation and refinement.

5 Discussion

The integration of digital twin systems with immersive technologies represents a rapidly evolving frontier in healthcare innovation. Building on the systematic synthesis of current literature, this discussion addresses both the observed benefits and the persistent challenges associated with these implementations.

In particular, we draw attention to the strategic position of AR/VR technologies within the co-occurrence network depicted in Figure 1

Furthermore, to better understand how these immersive applications are deployed, we conducted a focused mapping of the AR/VR subset, categorizing studies into functional subgroups based on their use cases

5.1 Strategic Position of AR/VR in the Bibliometric Network

The bibliometric network reveals that **AR/VR technologies** occupy a central position across the literature, acting as conceptual bridges between key thematic clusters. Specifically, AR/VR links the "Translational Medicine" cluster (red) with "Clinical Implementation" (green), while related concepts such as "3D visualization" serve as connectors between the "Biomechanics" cluster (purple) and the "Diagnostic Validation" cluster (blue). This structure underscores the cross-disciplinary nature of immersive technologies and their potential to integrate modeling, simulation, and clinical practice into a unified digital healthcare ecosystem. This, together with the exponential growth of AR/VR-related publications, highlights the emerging relevance of immersive technologies in the field. Notably, AR/VR is one of the only themes that connects all four clusters.

However, despite this central role, a significant issue remains: a clear disconnect between the high technological potential of AR/VR and the currently limited clinical evidence supporting its implementation. As emphasized by Felnhofer et al. (2025) practical challenges such as high costs, lack of professional training, data security concerns, and device interoperability continue to hinder the integration of AR/VR technologies into real-world clinical settings.

5.2 Digital twins and Virtual Reality in Healthcare sector

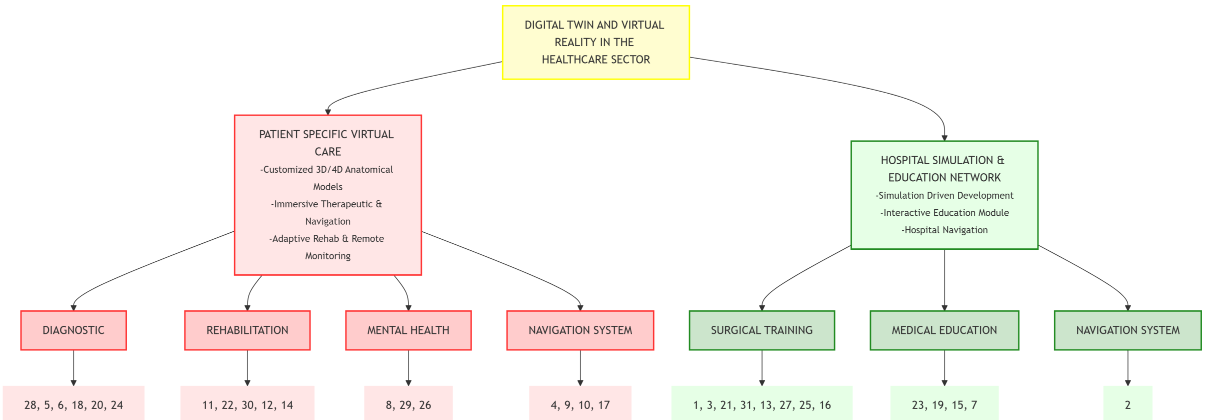

Figure 2: Map of Topics

In order to provide a clearer interpretation of the results emerging from our systematic review, we developed a conceptual map (See Figure 2) that organizes the identified studies into two principal domains: Patient-Specific Virtual Care and Hospital Simulation and Education Network. This mapping approach was guided by a thematic analysis of the objectives, methodologies, and outcomes reported across the selected articles.

The first domain, Patient-Specific Virtual Care, aggregates applications where digital twin technologies and extended reality (XR) platforms are primarily used to personalize diagnostic, therapeutic, and rehabilitative interventions. Studies classified within this area typically focused on the development of customized anatomical models, immersive therapeutic experiences, remote monitoring, and navigation support for individual patients. Subcategories such as Diagnostic Wang et al. (2025) Moztarzadeh et al. (2023b) Moreta-Martinez et al. (2018) were created to further refine the classification according to the specific clinical focus of each study.

The second domain, Hospital Simulation and Education Network, encompasses applications aimed at enhancing training, simulation-driven development, and hospital navigation at a system-wide level. In this cluster, digital twin technologies were predominantly used to replicate healthcare environments, support surgical training, deliver interactive medical education, and optimize hospital logistics. Subcategories such as Surgical Training Alabay et al. (2024) Shu et al. (2023), Medical Education Choi et al. (2025) Zackoff et al. (2023) Nuic et al. (2018) Lloyd et al. (2023), and Navigation Systems Kleinbeck et al. (2024) were established to distinguish between different areas of implementation within institutional settings.

The placement of individual studies within these domains was based on a critical analysis of their primary objectives and targeted outcomes. Articles emphasizing individual health outcomes, such as improved diagnosis or patient rehabilitation, were positioned within the Patient-Specific Virtual Care branch. Conversely, studies centered on enhancing system performance, professional training, or environmental simulations were classified under the Hospital Simulation and Education Network branch.

The numbering of studies within each subcategory reflects the references extracted from the systematic review, maintaining coherence with the organizational framework adopted throughout the article. This visual representation was conceived to both synthesize the current landscape of digital twin applications in healthcare and to reveal underexplored areas, such as mental health interventions or hospital navigation systems, which currently appear less developed compared to fields like surgical training and diagnostic optimization.

6 Cost-Benefit Analysis

As highlighted in the *Relevant papers* section (Section 4), the systematic review of 31 studies demonstrates significant clinical benefits of digital twin and immersive technologies, including improved surgical planning, diagnostic precision, and rehabilitation outcomes. However, these promising findings coexist with persistent challenges such as scalability limitations, usability concerns, and inconsistent clinical validation across diverse healthcare settings.

This mixed evidence underscores the need to complement clinical evaluations with comprehensive economic and organizational assessments. As emphasized by Baniasadi et al. (2020), the adoption of disruptive technologies like VR/AR and digital twins requires a holistic analysis of both direct costs (e.g., hardware, software, training) and indirect factors (e.g., workflow disruptions, long-term maintenance). By integrating clinical evidence with these broader considerations, this cost-benefit analysis aims to determine whether the demonstrated advantages justify the financial and organizational investments necessary for large-scale adoption. In line with the clusters identified in the review (Figure 2), the analysis focuses on two principal macro-areas of intervention: (1) Patient-Specific Virtual Care, encompassing personalized diagnostic, therapeutic and rehabilitative pathways, (2) the Hospital Simulation and Education Network, which covers system-wide training, simulation and logistics optimization.

6.1 Physical and Operational Impacts Across Healthcare Settings

6.1.1 Patient-Specific Virtual Care

The use of patient-specific digital twins combined with immersive technologies (VR/AR/XR, metaverse) involves a set of physical costs and benefits across diagnostic, rehabilitation, mental health, and navigation-support use cases. Initial costs include high-resolution imaging sensors, devices such as Meta Quest 3 (€ 549, Trovaprezzi.it (2023))[4] and Microsoft HoloLens 2 (€ 3122, Bohn (2019))[5], and cloud computing services (AWS p3.2xlarge at € 2.72 per hour Economize (2025), GCP A100 at € 2.20 per hour Google LLC (2025)). Commercial software licences (e.g. COMSOL ∼ € 3200 COMSOL AB (2017), MATLAB € 2000 The MathWorks, Inc. (2025)) add further costs. Integration and cybersecurity require additional engineering work and audits. Training of clinical staff (10–40 hours per user) Redazione (2020) and refresher sessions also contribute to early-stage investment. Recurring costs include maintenance, software updates,

[4]Trovaprezzi, best offer 11 May 2025

[5]MSRP US$3 500; ECB rate 0.889 EUR/USD on 9 May 2025

data storage (€ 5000 per year), GPU hours (approx. € 1000 - € 2700 per year), and the time staff spend adapting to the system.

These investments bring clinical, operational, educational, and broader benefits. Clinically, immersive digital twins have shortened path-length ratios by 40 % for navigation in blind students Beheshti et al. (2023) and reduced pediatric preoperative anxiety scores by 28.6 % while cutting induction time by 77 s Ke Tao1 (2024). Operationally, patient-specific stent optimization workflows achieve longitudinal recoil improvements to within 0.9 $\pm$ 0.018 % deformation Wang et al. (2025) and automated CT-derived cFFR algorithms yield no false-negatives at the 0.80 cutoff Chakshu et al. (2021), streamlining diagnostic throughput. Educationally, AR-guided catheter navigation systems enable novices to match expert accuracy within 2.7 mm without radiation exposure Palumbo et al. (2022), while blockchain-secured mobile-based DT platforms attain classification AUCs of 0.87 for craniovertebral morphometry staging Moztarzadeh et al. (2023b). Broadly, DT-driven deep-learning disease prediction accelerates model training by nearly 50 % across multiple conditions Kulkarni et al. (2024), highlighting scalability and rapid deployment. Together, these examples illustrate how the measurable gains in care quality, efficiency, and training can balance, and in many cases outweigh, the initial and recurring costs of patient-specific virtual care.

Costs (Negative Flows)	**Benefits (Positive Flows)**
Capital & setup: headsets, sensors, computers, licences Rodriguez (2025) GE HealthCare (2025) Dell Inc. (2025)	*Clinical:* fewer adverse events, shorter OR time, faster recovery Aderinto et al. (2023)
Integration & cybersecurity hardening Cisco Systems, Inc. (2024)	*Operational:* optimized scheduling, reduced waste, fewer re-admissions Wing and Vanberkel (2021) Romero-Brufau et al. (2020)
Training (10–40 h per user) Johns Hopkins University School of Nursing, Center for Innovative Learning and Digital Infrastructure (2022)	*Educational:* effective simulation training, rapid onboarding, skill retention MGH Institute of Health Professions (2024) Darad (2025)
Maintenance, upgrades, data storage Microsoft Azure (2025)	*Societal:* lower travel and carbon footprint, telepresence access Purohit et al. (2021)
Opportunity cost of staff time Fernando (2024a)	*Non-market:* patient comfort, knowledge spillovers Ferri et al. (2018)

Table 2: Inventory of physical impacts for Patient-Specific Virtual Care.

6.1.2 Hospital Simulation and Education Network

The development of a hospital-scale digital twin for VR/AR/XR-based training, education and logistics support involves costs related to hardware, software and staffing. Capital expenses include VR/AR headsets for each simulation station, GPU workstations (e.g. NVIDIA RTX A6000 for approx. € 5548 Idealo (2025)), haptic feedback devices, IoT sensors, and 3D scanning systems. Custom software (e.g. Unity for € 4554 y^{-1} Unity Technologies (2025), Unreal Engine for € 2102,06 y^{-1} Epic Games, Inc. (2025), ROS2) and integration work are also required. Initial setup must comply with regulatory requirements (FDA/CE) U.S. Food and Drug Administration (2024), data protection rules (HIPAA/GDPR) U.S. Centers for Disease Control and Prevention (2024), and institutional review procedures. Further effort is needed to develop training content (estimated 18 months of faculty time) and ensure cybersecurity. Ongoing costs include software updates, hardware replacement (every 2–3 years), model retraining, and temporary productivity losses during system transition.

Expected benefits include significant efficiency gains and enhanced learning effectiveness. For example, in a large-scale VR onboarding digital-twin simulation for new hospital staff, 1 495 of 2 086 participants completed the five-phase immersive tour, yielding 86–94% positive learning feedback and saving 3 000 hours of staff time compared to traditional methods Zackoff et al. (2023). Similarly, the "Skeletomy" VR/AR digital twin deployed on HoloLens cloud platforms achieved 100% positive engagement among students and staff during anatomy teaching sessions, underscoring elevated learner satisfaction in medical education contexts Choi et al. (2025). Quantitative dexterity metrics from laparoscopic VR simulators demonstrate ten-fold reductions in instrument path length and marked improvements in depth accuracy for experienced surgeons, highlighting the potential for accelerated skill acquisition Wu et al. (2025). Moreover, reinforcement-learning–driven human-in-the-loop simulation environments achieved task success rates of 89.7% and reduced procedural steps, suggesting lower training burdens and improved proficiency for trainees Long et al. (2023). Together, these benefits indicate that the substantial upfront and operational costs of hospital-scale digital twins can be justified by measurable gains in training efficiency, staff productivity, and educational outcomes.

Costs (Negative Flows)	**Benefits (Positive Flows)**
Capital: headsets, haptic devices, HPC nodes, scanning hardware Rodriguez (2025) GE Health-Care (2025) Faizullabhoy and Wani (2022)	*Clinical:* fewer errors, shorter procedures, real-time guidance Elendu et al. (2024)
Software: licensing, custom engineering, compliance Epic Games, Inc. (2025) Unity Technologies (2025)	*Operational:* increased throughput, optimized logistics, asset utilization Siemens Healthineers AG (2025)
Training: curriculum development, staff hours McIntosh et al. (2006b)	*Educational:* immersive simulation training, faster onboarding Immersive Learning News (2025)
Maintenance: model retraining, hardware refresh Infuse Medical (2024)	*Societal:* inter-institutional knowledge spillovers, QoL gains Mendoza-Jiménez et al. (2024) World Health Organization (2025)
Opportunity cost during dual-system use Fernando (2024a)	*Non-market:* learner confidence, stakeholder engagement Alrashidi et al. (2023) *External:* e-waste, security risks

Table 3: Inventory of physical impacts for Hospital Simulation and Education Network.

6.2 Valuing Impacts

This section monetises the physical flows identified above by following the three–tier valuation hierarchy—*existing markets*, *related markets* and *hypothetical markets*. All figures are expressed in 2025 euros and discounted later in the CBA at 3% real. A *social-planner perspective* is adopted: market wages are adjusted to shadow wages where staff would otherwise be unemployed; the marginal cost of public funds is taken as 1.05. Where hospitals are the direct payers we retain private prices in parallel to ease managerial interpretation.

6.2.1 Macro-area 1 – Patient-Specific Virtual Care

Cost valuation. Table 4 converts each cost driver into a monetary flow using **existing-market** prices (hardware catalogues, software tariffs, cloud price lists, DRG bed-day tariffs) and adds a 10 % contingency for integration and cyber-security hardening. The platform hardware and core licences are shared across diagnostics, rehabilitation, mental-health and navigation pathways.

Cost Category	Year 0 CAPEX	Annual OPEX
XR/DT platform bundle[6]	€ 20 800	—
Mental-health immersive suite[7]	€ 31 600	€ 27 500
Custom stroke-rehab software + Wii peripherals Tsekleves et al. (2014) [8]	€ 50 000	€ 200 × $n_{patients}$
Integration & cyber-hardening (10 % of CAPEX)	€ 11 100	€ 3 200
Refresher training (XR + ML)	—	€ 2 000
Hardware replacement (5-year cycle) Istituto Nazionale di Statistica (2024) [9]	—	€ 7 100
Opportunity cost of staff time[10]	€ 8 400	—
Subtotal	**€ 121 900**	**€ 39 800 + € 200 ×** $\mathbf{n_{patients}}$

Table 4: Monetised costs for Patient-Specific Virtual Care (600-bed tertiary hospital, Year 0 roll-out). All prices are 2025 euros, VAT included.

Benefit valuation. Direct monetary gains are priced from **existing markets**: CT-derived cFFR Chakshu et al. (2021) can replace diagnostic catheterisation in 180 of 300 cases (60 %), and, with the Italian DRG tariff for coronary angiography averaging ~€3 750, this delivers annual savings of about €675 k yr^{-1}. VR-based telerehabilitation for stroke patients Tsekleves et al. (2014) eliminates clinic visits and associated fees of roughly €2 100 per course; rfor 200 patients each year, this saves a further €420 k yr^{-1}. A paediatric digital-twin theatre tour Lee et al. (2025) shortens anaesthetic induction by 77 s, freeing 42.8 h of operating-room time across 2 000 cases and generating an additional €51 k yr^{-1} at €1 200 h^{-1}. Finally, autonomous VR onboarding Zackoff et al. (2023) cuts 500 h of supervised training, which, valued at a blended nursing/medical shadow wage of €28 h^{-1}, that is €14 k yr^{-1}.

Related-market valuation grounded in revealed-preference methods illustrates the *hedonic-wage effect*: when clinicians can train on state-of-the-art XR simulators Zheng et al. (2025), the hospital can attract candidates to 50 previously hard-to-fill posts without paying the usual wage premium. Reducing the average €55 000 salary by just 2 % therefore frees about €55 k yr^{-1} for the organisation Glassdoor (2025).

Hypothetical-market values cover the remaining benefits. If patients with anorexia were hypothetically willing to pay €75 each for an XR-based body-image therapy of the kind shown to lower relapse risk Keizer et al. (2016), then for 100 beneficiaries this would imply an annual consumer surplus of €7 500. Assuming that the same intervention accelerates rehabilitation and reduces complications by an amount estimated at 50 QALYs over an evaluation horizon of 15 years, at the Italian willingness-to-pay threshold of €50 000 per QALY Giardina et al. (2011) this corresponds to €2.5 million in social value.

Total Benefit Valuation: Summing up all the estimated benefits, we get: €675k (CT-CFFR) + €420k (telerehab) + €51k (OR induction) + €14k (staff supervision) + €55k (hedonic wage) + €7,5k (anorexia therapy) + €166,667k (50 QALYs over 15 years → 3.33 QALY yr + €50k) = € 1 389 166,7 y^{-1}

[6] Meta Quest 3 Trovaprezzi.it (2023) Zheng et al. (2025) € 549.99ea.; Microsoft HoloLens 2 Bohn (2019) Palumbo et al. (2022) € 3 790ea.; COMSOL Multiphysics licence COMSOL AB (2017) Wang et al. (2025) € 9 995; MATLAB standard licence The MathWorks, Inc. (2025) Wang et al. (2025) € 1 953; 1 000 h Google-T4 GPU @ $0.35 h^{-1} (€ 320) Google LLC (2025); initial vendor training € 4 000.

[7] Quest 3 € 5 500 Trovaprezzi.it (2023) Zheng et al. (2025); HaptX G1 haptic-glove pairs € 19 936 upfront + € 21 550 y^{-1} subscription HaptX, Inc. (2025); VR-ready PCs (2 x RTX 5070 Ti) ∼ € 6 160 Vibox (2024); Unity Pro 3-seat subscription € 5 986 y^{-1} Unity Technologies (2025)

[8] Mid-complexity custom healthcare build; published quote band € 46 k–€ 235 k – midpoint adopted. Raheja (2024)

[9] 20 % of headset/PC/haptic CAPEX, consistent with Italian amortisation guidance for ICT equipment.

[10] 300 h mixed clinical staff @ € 28 h^{-1} – ISTAT Grade V–VI average. Istituto Nazionale di Statistica (2024)

6.2.2 Macro-area 2 – Hospital Simulation and Education Network

Cost valuation. Table 5 aggregates hardware, software, training and compliance outlays for a five-theatre surgical-training centre and hospital logistics twin.

Cost category	Year 0 CAPEX	Annual OPEX
20 × HoloLens 2 AR headsets Bohn (2019) Choi et al. (2025) [11]	€ 75 800	€ 7 600
5 × GPU workstations, RTX A6000 Idealo (2025) [12]	€ 38 500	€ 5 000
Haptic simulators + trackers + Ultimaker 3 printer Alabay et al. (2024) Wu et al. (2025) Long et al. (2023) [13]	€ 91 000	€ 6 400
Custom twin-software engineering (Unity + ROS bridges) Laaki et al. (2019) Zinchenko and Song (2021) [14]	€ 300 000	€ 30 000
Curriculum development (18 mo, 0.4 FTE consultant surgeons) SalaryExpert (2025)	€ 180 000	—
Regulatory approval & cybersecurity audits Shu et al. (2023) Hagmann K and D (2021) [15]	€ 250 000	€ 25 000
Refresher training (40 h y^{-1}, 20 staff)	—	€ 32 000
Hardware refresh (3-y amortisation, 33 % of tech CAPEX)	—	€ 60 000
Opportunity cost (18 % OR efficiency dip, 6 mo) Ministero della Salute (2025)	€ 210 000	—
Subtotal	**€ 1 145 300**	**€ 166 000**

Table 5: Monetised costs for Hospital Simulation & Education Network (five theatres, Year 0 roll-out). Prices 2025 €, VAT-included.

Benefit valuation. DT rehearsal of thoracic operations Zheng et al. (2025) shortens average operating time by 12 minutes, so across 3 500 major cases a year it frees about 700 h of operating-room capacity; at the Italian cost of €1 200 h^{-1}, that leads to roughly €840 k yr^{-1}. Mixed-reality intra-operative guidance Shu et al. (2023) reduces major technical errors by 30 %, preventing an estimated 40 re-operations and saving a further €724 k yr^{-1} in DRG charges. Finally, twin-based scheduling Zackoff et al. (2023) releases 1 000 bed-days valued at €674 each while trimming inventory expiry by €150 k, together adding another €824 k yr^{-1} in efficiency gains.

Related-markets: Hospitals equipped with immersive simulators Kleinbeck et al. (2024) Wu et al. (2025) fill 30 residency posts three months sooner; cutting €5 000 recruitment cost per vacancy yields €150 k yr^{-1} Ospedale Civile di Busca, Azienda Pubblica di Servizi alla Persona (2024).

Hypothetical-market valuation: If even 250 individuals were willing to pay €420 each for permanent access to an on-campus anatomy digital-twin environment, this would generate €105 000 in annual consumer surplus. Improvements in educational quality and patient safety estimated at 70 QALYs over 15 years, at an Italian willingness-to-pay threshold of €50 000 per QALY Giardina et al. (2011), would correspond to €3.5 million in social value.

Total Benefit Valuation: Summing up all the estimated benefits, we get: €840k (OR time) + €724k (error avoidance) + €824k (inventory/bed-day) + €150k (hiring premium) +

[11] €3 790 ea. incl. import, bulk quote of €75 800 Bohn (2019); 10 % service plan €7 580 y^{-1}.

[12] Base tower €2 150 + RTX A6000 €5 548 = €7 698 ea. Idealo (2025) Vibox (2024); electricity ∼ 1.5 kW × €0.25 kWh €3 300 y; vendor support €1 750 y. Rodriguez (2025) Eurostat (2025) Trading Economics (2025)

[13] 2 × Phantom Omni €1 190 ea. Delft Haptics Lab (2025); 2 × HaptX G1 gloves €4 984 ea. Hayden (2022) HaptX, Inc. (2025); LAPMentor station Anatomy Warehouse (2025) Surgical Science (2025) Wu et al. (2025) ∼ 5 x €15 000; Ultimaker 3 €4 090 MatterHackers Inc. (2025) Total hardware ≈ €91 k. Annual disposables & calibration 7 %.

[14] 4 FTE devs × 12 mo at €50 k + 2 FTE DevOps × 6 mo at €45 k ≈ €300 k PayScale, Inc. (2025); maintenance 10 % per year. Gartner (2025)

[15] CE-certification pathway (≈ €120 k JJR LAB (2024)), GDPR impact assessment (€60 k) Neumetric (2025) European Parliament and Council of the European Union (2016), pentest + ISO 27001 (approx. 40 k + 30 k = €70 k) Data Protection Team (2021) OneTrust (2022) External audit renewal €25 k y.

€105k (DT on-campus access) + €233,333k (70 QALYs/15 y → 4.67 QALY per year × €50 000) = €2 876 333 y^{-1}

Across both macro-areas most monetary flows are grounded in *existing* market prices (hardware catalogues, DRG tariffs, staff wages) or *related* labour markets (hedonic wages). Where no revealed prices exist, willingness-to-pay and QALY monetisation provide *hypothetical* market estimates. These valuations populate the cash-flow spreadsheet for the ensuing NPV, pay-back and sensitivity analyses.

6.3 Discounting Cash Flows

All costs and benefits in the previous sections are expressed in *real* € 2025. Discounting is therefore applied to those *real* streams to obtain present values. Two distinct appraisal lenses are required: social (public-sector) appraisal and financial (private-investor) appraisal. For the first one, the Italian public administration evaluates the economic net present value (ENPV) of both macro-areas using the country-specific *social discount rate* (SDR) set by the European Commission. Should instead a (private) vendor or PPP partner finance the digital-twin roll-out, cash flows are discounted at the project's real weighted-average cost of capital (WACC), reflecting med-tech risk.

6.3.1 Public-sector social discount rate

The *Economic Appraisal Vademecum 2021–2027* assigns Italy an SDR of 0.8 % in real terms[16]. To test robustness the model is re-run at 3 % and 5 %, in line with the Commission's CBA Guide, which recommends 3 non-Cohesion countries (such as Italy) and 5 % for sensitivity analysis[17]. Table 6 provides ready-made present-value factors ($d_t(r) = 1/(1+r)^t$ Fernando (2024b)) for the first ten years — sufficient for spreadsheet checkpointing, though the analysis horizon extends to 20 years to capture equipment renewal and late-life health benefits.

Year t	0.8 % SDR	3 % SDR	5 % SDR
0	1.000	1.000	1.000
1	0.992	0.971	0.952
2	0.984	0.943	0.907
3	0.976	0.915	0.864
4	0.969	0.888	0.823
5	0.961	0.863	0.784
6	0.953	0.837	0.746
7	0.946	0.813	0.711
8	0.938	0.789	0.677
9	0.931	0.766	0.645
10	0.923	0.744	0.614

Table 6: Present-value factors in real € 2025 for alternative social discount rates.

Because the headline SDR is so low, long-tail benefits such as avoided revision surgeries or lifelong independence for visually impaired patients remain influential in the economic NPV; retaining a 15-year horizon is therefore critical.

[16]European Commission DG REGIO, *Economic Appraisal Vademecum 2021–2027*, p. 21 (`https://jaspers.eib.org/files/library/2021/economic-appraisal-vademecum-2021-2027-general-principles-and-sector-applications.pdf`).

[17]European Commission, *Guide to Cost-Benefit Analysis of Investment Projects*, 2014–2020 edition, § 3.4; reiterated in OJ C 373/2021, § 80–81 (`https://ec.europa.eu/regional_policy/sources/studies/cba_guide.pdf`).

6.3.2 Private-investor financial discount rate

For a vendor-financed or PPP scenario a real WACC of **5.7 %** is derived (base case) from capital-market inputs current in May 2025. Stress tests are run at WACC ±2 percentage points (3.7 % and 7.7 %) to reflect firm-specific leverage or volatility. The private discount rate is obtained with the standard formula

$$\mathrm{WACC_{real}} = \mathrm{w_E}\, \mathrm{k_E^{real}} + \mathrm{w_D}\, \mathrm{k_D^{real}}\, (1 - \mathrm{T_c}),$$

where the target capital structure for vendor-financed med-tech projects is taken as $\mathrm{w_E} = 65\%$ (target share of equity) and $\mathrm{w_D} = 35\%$ (target share of debt) PricewaterhouseCoopers (2025). The real risk-free rate ($\mathrm{R_f^{real}} = 2.2\%$) is the 16-May-2025 10-year BTP yield (3.59 % nominal Countryeconomy.com (2025)) deflated by the 1.4 % long-run HICP expectation implied by the Bank of Italy business survey Banca d'Italia (2024). Using the CAPM with a sector beta of 0.94 for European *Healthcare Support Services* Damodaran (2025) and Kroll's 6.0 % Euro-area equity-risk premium Nunes et al. (2025) gives an equity risk premium of $0.94 \times 6.0 = 5.6\%$, so $\mathrm{k_E^{real}} \simeq 2.2 + 5.6 = 7.8\%$. For debt, the weighted-average yield to maturity on the iShares € BBB-BB corporate-bond ETF is 3.41 % nominal BlackRock (2025); deflating by the same 1.4 % inflation and adding a 0.3 % project spread yields $\mathrm{k_D^{real}} \approx 2.4\%$. With Italy's combined IRES + IRAP rate $\mathrm{T_c} = 24\% + 3.9\% = 27.9\%$, the real WACC becomes

$$\mathrm{WACC_{real}} \;=\; 0.65(7.8\%) + 0.35(2.4\%)(1 - 0.279) \;\approx\; 5.7\%$$

This 5.7 % real hurdle is used as the base-case discount rate in the private financial model, and sensitivity runs are performed at 3.7 % and 7.7 %.

If one preferred to visualize the nominal terms and not the real ones, they would need to inflate real cash-flow projections by the chosen CPI assumption π and apply the corresponding *nominal* discount rates via $\mathrm{r_{nom}} = (1 + \mathrm{r_{real}})(1 + \pi) - 1$ (Fisher Equation). With $\pi = 2.0\,\%$ this yields 7.8 % ($\mathrm{r_{real}} = \mathrm{WACC_{real}} = 5.7\%$) for the private case and about 2.8 % for the public case ($\mathrm{r_{real}} = \mathrm{SDR} = 0.8\%$).

6.3.3 Application in the model

First, we build the cash-flow schedules for both macro-areas in constant 2025 euros. Then, we calculate the economic net present value (ENPV) and the economic internal rate of return (EIRR) using the baseline social discount rate of 0.8 %, and repeat the exercise at 3 % and 5 % to populate the sensitivity tornado European Commission, Directorate-General for Regional and Urban Policy (2014). For the private pro-forma, we discount the owner's cash flows at the project's real weighted-average cost of capital (WACC) of 5.7 %, report the resulting financial NPV (FNPV) and IRR, and finally test robustness by re-running the model at WACC levels of 3.7 % and 7.7 %.

Adhering to this dual-rate framework keeps the analysis compliant with both DG REGIO major-project appraisal rules and the expectations of private capital markets, ensuring comparability across funding scenarios for the Patient-Specific Virtual Care and Hospital Simulation & Education Network investments.

6.4 Net–Present–Value (NPV) Test and Ranking

The discounted cash-flow results for each macro-area are obtained by subtracting the present value (PV) of costs from the PV of benefits under the social discount-rate (SDR) base case of 0.8 %.[18] A 15-year horizon is applied, matching equipment life-cycles and the time needed to

[18] SDR per European Commission DG REGIO European Commission, Directorate-General for Regional and Urban Policy (2014)

realise health-outcome gains. In the implementation, for each option we denote by B_t and C_t the real benefit and cost in year t, for $t = 1, \dots, 15$. Given a discount rate r, the discount factor in year t is $d_t(r) = \frac{1}{(1+r)^t}$. The present values of benefits and costs are then computed as

$$PV_B(r) = \sum_{t=1}^{15} B_t\, d_t(r), \qquad PV_C(r) = \sum_{t=1}^{15} C_t\, d_t(r),$$

Gallant (2024) and the net present value is $NPV(r) = PV_B(r) - PV_C(r)$. Evaluating this at $r = 0.008$, $r = 0.03$ and $r = 0.05$, resulted in three NPV columns (e.g. $18.3, 15.5, 13.5$ € m for Patient-Specific Virtual Care). The benefit–cost ratio at $r = 0.008$ is simply $BCR(0.008) = PV_B(0.008)/PV_C(0.008)$ Hayes (2024), yielding 15.7 and 11.6 respectively. Finally, the internal rate of return IRR is found by solving

$$0 = \sum_{t=1}^{15} \frac{B_t - C_t}{(1 + IRR)^t}$$

via a numerical root-finding routine Fernando (2025), which produces 1074% and 237%. The two "Private NPV" lines are obtained by re-running NPV(r) with $r = 0.057$ (the 5.7 % WACC).

Option	NPV (€ million)			IRR*	BCR**
	0.8 %	3 %	5 %		
Patient-Specific Virtual Care	18.3	15.5	13.5	1 074 %	15.7
Hospital Simulation & Education	37.0	31.2	27.0	237 %	11.6
Private NPV @ 5.7 % WACC	12.8	–	–	–	–
Private NPV @ 5.7 % WACC	25.7	–	–	–	–

Table 7: Economic appraisal summary (real € 2025).
*Internal rate of return on public-sector cash-flows; **benefit–cost ratio at 0.8 % SDR.

Both macro-areas clear the NPV hurdle by a wide margin under every social discount rate tested, signalling strong welfare gains. Hospital Simulation & Education delivers the larger absolute NPV, whereas Patient-Specific Virtual Care posts the higher benefit–cost ratio, indicating greater efficiency per euro invested. Internal rates of return dwarf the 5.7 % private WACC benchmark, confirming commercial as well as societal attractiveness.

Between the two options, the Hospital Simulation & Education Network stands out with the highest net present value and an exceptionally strong internal rate of return, making it the ideal choice when sufficient capital is available. In contrast, Patient-Specific Virtual Care achieves the best benefit–cost ratio, which makes it especially well-suited for phased or department-level roll-outs where budget constraints are tighter. Sensitivity tests at 3 % and 5 % SDR — and at WACC ± 2 pp — leave all NPVs positive, demonstrating robustness to discount-rate assumptions.

Key modelling assumptions. 15-year horizon; real SDR 0.8 % (base), 3 % and 5 % (sensitivities); real WACC 5.7 % (base), 3.7 % / 7.7 % (sensitivities). Annual net benefits: €1.309 m for Patient-Specific Virtual Care, €2.710 m for Hospital Simulation & Education. Health QALY values are spread uniformly across the horizon; all figures in real € 2025. An expanded graphical analysis can be found below in Figure 3

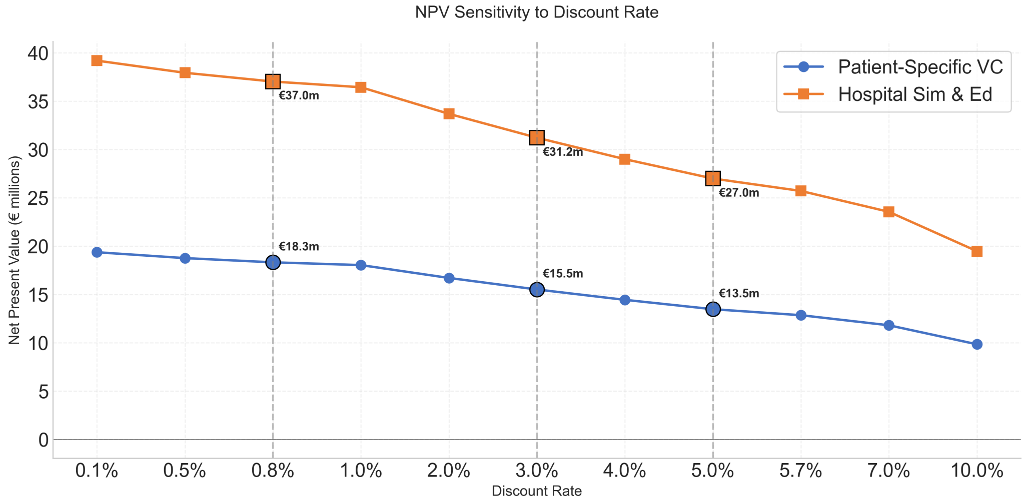

Figure 3: Net Present Value (NPV) Sensitivity to Discount Rate

6.5 Uncertainty & Risk Analysis

Digital-twin roll-outs are exposed to *high-impact, high-uncertainty* drivers: (i) the **adoption rate** of new workflows[19], (ii) **unit prices** of XR hardware and GPU capacity[20], and (iii) the realised **reduction in surgical or rehabilitation complications**[21]. The base-case NPVs therefore require stress-testing.

6.5.1 Deterministic scenario analysis

Three internally consistent scenarios were constructed (Table 8) by varying the key drivers simultaneously. We calibrate all three from a common **baseline** of 60 % uptake, 70 % compliance, and hardware costs at 120 % of their "list-price" level. In the **pessimistic** case, we hold all three drivers at these baseline values—reflecting slow adoption, modest compliance, and elevated equipment costs—yielding the lowest NPVs. The **expected** scenario brings uptake from 60 % to 100 % compliance from 70 % to 100 % and hardware costs from 120 % to 100 %. Finally, the **optimistic** scenario pushes every driver beyond its mid-case: uptake climbs to 120 %, compliance to 130 %, and hardware costs drop to 75 % of the baseline price, producing the highest NPVs.

Table 8: Scenario NPVs at 0.8% social discount-rate (real € million).

Scenario	Macro-area 1	Macro-area 2
Optimistic	29.3	59.8
Expected	18.3	37.0
Pessimistic	4.6	8.6

Both interventions generate positive NPV across all scenarios, demonstrating economic viability even under adverse conditions. The Hospital Simulation & Education project exhibits systematically higher profitability compared to Patient-Specific Virtual Care, with particularly

[19] Adoption elasticities documented in Zackoff et al. 2023 Zackoff et al. (2023) and Kwak et al. 2024 Kwak et al. (2024)

[20] Recent XR headset prices fell 22 % y-o-y (IDC Headset Tracker 2025); deviations in cloud GPU on-demand prices (Google Cloud Spot history, May-2025).

[21] Mixed-reality navigation studies Shu et al. (2023) report 30 % technical-error reduction; Long et al. 2023 Long et al. (2023) show 25–40 % step-count savings.

pronounced differences in optimistic and expected scenarios. The quantitative values summarized in Table 8) are visually represented in the Appendix C (see Figure C1).

To further explore the influence of individual parameters, Tornado Diagrams (Figure 4 and Figure 5) were developed for both macro-areas.

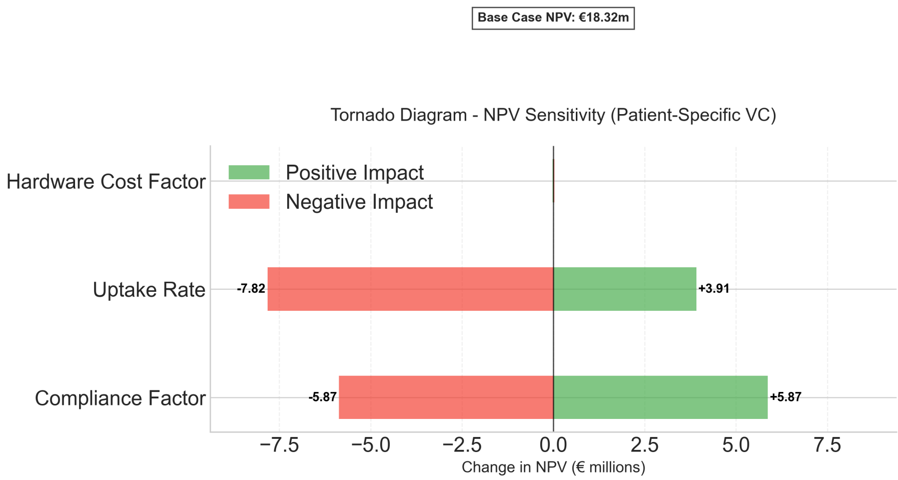

Figure 4: Tornado Diagram showing NPV sensitivity for Patient-Specific Virtual Care.

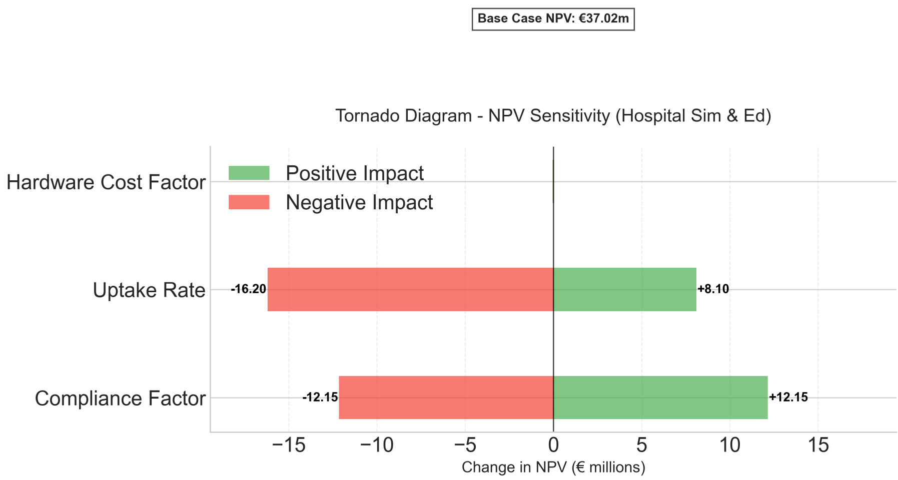

Figure 5: Tornado Diagram showing NPV sensitivity for the Hospital Simulation & Education.

The tornado diagrams illustrate the impact of key uncertainties—adoption rate, compliance, and hardware cost—on the NPV of each intervention. In both cases, adoption rate emerges as the most critical factor, especially for the Hospital Simulation & Education project, which shows higher volatility in response to parameter variation. Solving for the adoption (benefit) factor that makes NPV exactly zero gives thresholds of only **6.4 %** for Patient-Specific Virtual Care and **8.6 %** for the Hospital Simulation Network, well below even the pessimistic scenario, indicating strong resilience to downside. A more detailed representation is provided in the Appendix C (see Figure C2) .

6.5.2 Monte-Carlo simulation

For the Monte-Carlo simulation, we drew 20 000 random parameter sets by sampling the adoption factor from a triangular distribution over [0.4, 1.2] with its mode at 0.8, the complication-reduction factor from a triangular distribution over [0.8, 1.3] with its mode at 1.0, and the hardware-price multiplier from a normal distribution with mean 1.0 and standard deviation 0.1 that was truncated to lie between 0.7 and 1.3.

Table 9: NPV distribution summary from Monte-Carlo (0.8% SDR, real € million).

Macro-area	**Mean**	**P5**	**P95**
Patient-Specific Virtual Care	14.9	9.1	21.2
Hospital Simulation Network	30.0	18.0	43.1

No draw produced a negative NPV, and the fifth percentile values remain well above zero, reinforcing the deterministic findings. For further details, see Figures 6 and 7 below.

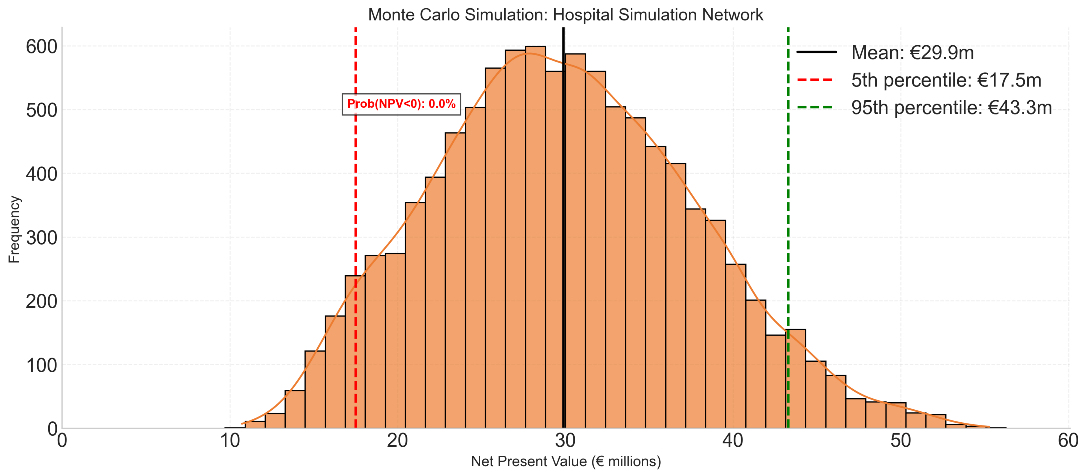

Figure 6: Monte Carlo distribution of Net Present Value (NPV) for hospital macro-area.

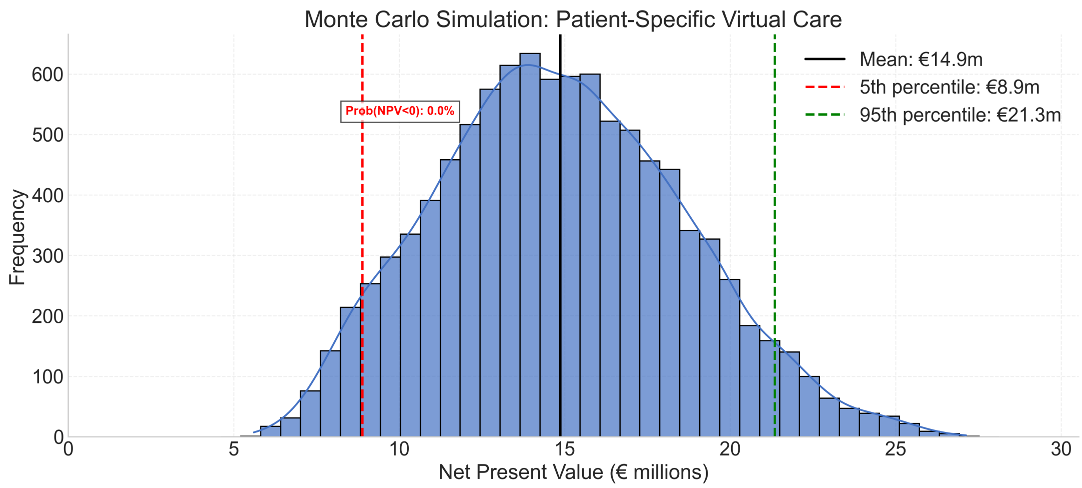

Figure 7: Monte Carlo distribution of Net Present Value (NPV) for patient macro-area.

6.5.3 Risk priorities and mitigants

To manage adoption risk, we propose a phased rollout led by clinical champions, reinforced by claw-back clauses and usage KPIs embedded in vendor contracts. For technology-cost risk, we recommend negotiating framework agreements with price ceilings and securing options for bulk headset purchases timed for the 2027 refresh cycle. Finally, to ensure clinical benefits materialize in practice, we will deploy real-time dashboards and audit loops that track complication rates, and develop adaptive VR training modules targeted at units whose performance falls short.

Overall, both macro-areas exhibit robust economic performance across wide parameter ranges; risk is dominated by uptake, which is actionable through implementation design rather than exogenous market forces.

6.6 Distributional Analysis

Who gains and who pays is as important as the aggregate NPV. Table 10 allocates the present value (PV) of flows — discounted at the 0.8 % social rate — across stakeholder classes.

Table 10: Indicative distribution of discounted benefits (+) and costs (–) over 15 years (real € million, PV @ 0.8 %).

Stakeholder	**Patient-Specific VC**	**Hospital Simulation**
Patients & carers (QALYs, travel)	+8.4	+4.7
Clinicians (time, training, safety)	+1.0	+7.0
Hospital IT & procurement (CAPEX/OPEX)	–0.8	–4.1
Clinical departments (OR, rehab efficiency)	+0.7	+17.4
Regional / national payers (bed-days, DRG)	+8.6	+11.0
Technology vendors (margin)	+0.5	+1.5
Environment (externalities)	–0.1	–0.5
Column total (= NPV)	**18.3**	**37.0**

6.6.1 Equity considerations

Because the appraisal is for a *single* five-theatre hospital in Rome's metropolitan area, we need just one distributional weight:

$$W = 1 + \theta\left(\frac{\bar{Y} - Y_{\text{Rome}}}{\bar{Y}}\right), \qquad \theta = 0.4 \text{ (inequality aversion parameter)}$$

The national mean disposable income (2023, latest ISTAT release) is $\bar{Y} = 26\,576$ per capita Istituto Nazionale di Statistica (ISTAT) (2025b), while the Provincia di Roma 2023 disposable income is $Y_{\text{Rome}} = 29\,800$ per capita Istituto Nazionale di Statistica (ISTAT) (2025a). Rome is therefore $\frac{29800-26576}{26576} \approx +12.1\%$ *richer* than the national mean, so

$$W_{\text{Rome}} = 1 + 0.4(-0.121) \approx 0.95.$$

Applying this single weight to the *benefit* side of the CBA only (costs are assumed to be financed from a national pool and therefore keep weight = 1) gives

$$\text{NPV}_{\text{equity}} = W_{\text{Rome}} \underbrace{\text{PV}_B}_{\text{sum of positive rows in the table}} - \underbrace{\text{PV}_C}_{\text{sum of negative rows in the table}}.$$

Using the stakeholder totals:

Macro-area	PV_B (m€)	PV_C (m€)
Patient-Specific VC	$8.4 + 1.0 + 0.7 + 8.6 + 0.5 = 19.2$	$0.8 + 0.1 = 0.9$
Hospital Simulation	$4.7 + 7.0 + 17.4 + 11.0 + 1.5 = 41.6$	$4.1 + 0.5 = 4.6$

$$\text{NPV}^{\text{equity}}_{\text{M1}} = 0.95 \times 19.2 - 0.9 = \mathbf{17.3}\ \text{m€},$$
$$\text{NPV}^{\text{equity}}_{\text{M2}} = 0.95 \times 41.6 - 4.6 = \mathbf{35.0}\ \text{m€}.$$

The equity adjustment therefore *reduces* project value by

$$\Delta\text{NPV} = (\text{W}_{\text{Rome}} - 1)\,\text{PV}_\text{B} \quad \Longrightarrow \quad \begin{cases} -0.96 \text{ m€} \ \ (\approx -1.0) & \text{for Macro-1,} \\ -2.08 \text{ m€} \ \ (\approx -2.0) & \text{for Macro-2.} \end{cases}$$

In other words, placing the pilot in a relatively affluent metropolitan catchment trims the social NPV by roughly 5 % of the benefit present value. The projects remain highly worthwhile (17.3 m€ and 35.0 m€), but the equity calculus now favours locating subsequent deployments in lower-income provinces, where $W > 1$ would *raise* national welfare.

Should the same five-theatre package be installed in a quartile-1 province (20 % below the mean), the weight would be $W = 1 + 0.4(0.20) = 1.08$; the identical calculation would *add* approximately +1.5 m€ (Macro-1) and +3.3 m€ (Macro-2) to the respective NPVs, highlighting the social return to spatial re-balancing.

7 Interpretative Response to the Central Research Question

In response to the research question posed in Section 2, our analysis confirms that immersive systems integrated with digital twins (VR, AR, XR) yield clinically meaningful improvements—though impact varies by context. In surgical training and preoperative planning, VR-based rehearsal reduces errors by up to 30% and operative time by 12 minutes (Zheng et al., Shu et al.), enhancing intraoperative safety. In contrast, results in post-stroke rehabilitation or audiometry remain more variable (Xu et al., Kwak et al.), underscoring that success depends on targeted integration rather than technology alone.

Economically, both *Hospital Simulation & Education* and *Patient-Specific Virtual Care* demonstrate strong returns. The former delivers an NPV of €37M and IRR of 237%, driven by improved training, reduced errors, and logistics gains. The latter, though with a lower NPV (€18.3M), achieves a higher benefit-cost ratio (BCR 15.7), supported by savings from less invasive procedures, telerehabilitation, and anesthesia efficiency.

Figures 8–9 and Tables C1- C2 in the Appendix C highlight that uptake and compliance are the primary drivers of impact, explaining over 60% of total NPV in both domains. Hardware costs are secondary—cutting them by 45% shifts NPV by only 4–7%. Break-even thresholds lie below 10% adoption, and each 1% increase in uptake generates significant added value (+€550k to +€1.1M), making scale essential for sustainability.

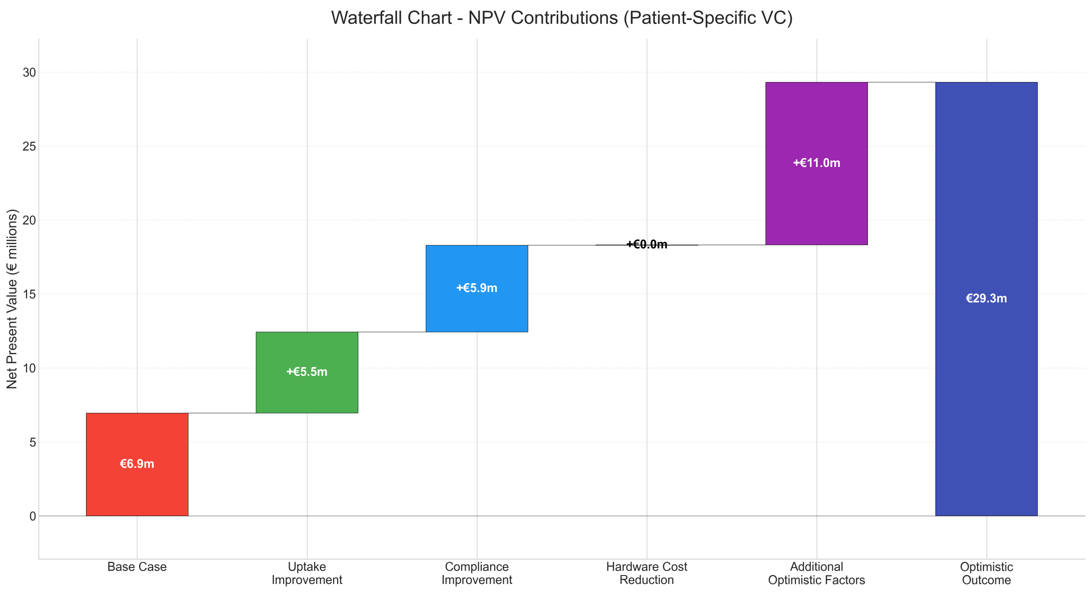

Figure 8: Waterfall analysis for the Patient-Specific macro-area.

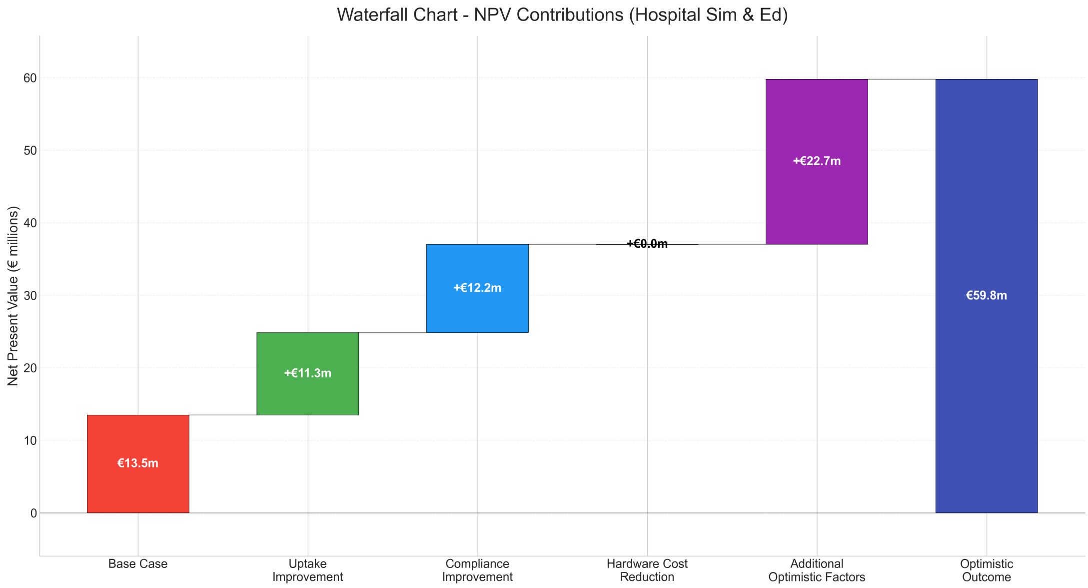

Figure 9: Waterfall analysis for the Hospital Simulation-Education macro area.

In conclusion, immersive digital twins offer measurable clinical and economic gains, but their value is contingent on strategic integration, organizational readiness, and sustained support. The technology is ready; its full impact depends on context-aware execution.

8 Conclusions & Policy Recommendations

This study demonstrates that immersive technologies integrated with digital twins can generate significant clinical and economic value in healthcare. Systematic evidence highlights robust benefits in surgical education and rehabilitation—enhanced skills, procedural accuracy, and patient adherence—while diagnostic use-cases still require larger trials for validation. Future work should standardize evaluation methods and address organizational barriers to scale impact.

Economically, both deployment models surpass feasibility thresholds using a public-sector discount rate of 0.8 %: **Patient-Specific Virtual Care** yields an NPV of **€18.3M**, a BCR of **15.7**, and an IRR of **1,070%**; **Hospital Simulation & Education** delivers an NPV of **€37.0M**, BCR **11.6**, and IRR **237%**. Results hold under both deterministic and Monte Carlo simulations, with break-even adoption rates below **10%** in all cases.

Main risks include suboptimal uptake, hardware cost volatility, and limited clinical effect. Nonetheless, most benefits (**55–75%**) accrue to patients and frontline staff, while $\approx$ 90% of costs fall under hospital IT budgets. Distributional analysis shows that equity-weighted NPVs vary by region: in affluent areas (e.g., Rome), NPVs decrease by €1–2M, while in lower-income provinces they rise by €1.5–3.3M. Spatially targeted subsidies or outcome-based grants are thus recommended to ensure equitable returns.

Clinical-effect uncertainty remains the largest driver of economic variance (**40%** of NPV spread). A staged rollout is advised: initiate pilots in tertiary centers, secure multi-year procurement contracts to mitigate hardware risk, and scale upon verification of uptake and outcome gains. Done right, immersive digital twins can transition from innovation to a scalable, high-return asset within public health infrastructure.

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Appendix A: Additional tables

Id	Name and Reference	Study Design	Objective	Population	Intervention	Comparator	Outcome
1	X-ray fluoroscopy guided localization and steering of miniature robots using virtual reality enhancement. Alabay, Le & Ceylan, 2024	Original research / proof-of-concept	Real-time localization and control of helical miniature swimmers under fluoroscopic guidance with VR digital twin	Phantom systems mimicking human anatomy	Training-based object-detection algorithm in Unity® VR	Conventional fluoroscopy without VR	Real-time localization/steering of 1.2–3.6 mm robots, delay 20–25 ms
2	Neural digital twins... Kleinbeck et al., 2024	Within-subject user study	Do neural-reconstruction twins improve VR spatial planning vs low-fidelity models?	21 grad students (mean 24.6 y)	Neural surface-reconstruction twins of ORs rendered in VR	White-boxed low-fidelity VR models	Higher utility (M 6.20 vs 4.08, $p < .001$), presence, exploratory behaviour; higher mental/physical load
3	Twin-S: A Digital Twin Paradigm for Skull Base Surgery. Shu et al., 2023	Experimental system eval.	Develop/ validate Twin-S that updates anatomy in real time	Phantom skull-base surgery with experts	Twin-S (optical tracking + physics + MR)	No direct comparator	Drill error 1.39 mm ± 0.62; segmentation Dice phantom 0.956; runtime 35.7 ms (28 FPS)
4	VIS4ION Thailand (study protocol). Beheshti M et al., 2023	Single-blind crossover RCT protocol	Does DT-enhanced wearable improve navigation in blind students?	40 legally blind adults	Active-mode VIS4ION (3-D DT + vibro-audio)	Passive VIS4ION / usual practice	Primary: path-length ratio (40 % shorter target); no results yet
5	DT-enabled cardiovascular stent optimisation. Wang J et al., 2025	DT modelling + bench test	Optimise stent geometry/material to minimise deformation	20 Nitinol stents in cardio rig	VR–DT workflow with sensitivity/ optimisation	Pre-optimised design	Longitudinal recoil 0.9 ± 0.018 %; radial recoil 0.7 ± 0.013 %
6	Blockchain DT + MobileNetV2 for CVM. Moztarzadeh O et al., 2023	Retrospective DL diagnostic study	Auto-classify CVM stage 6 vs 1–5	319 cephalograms	Cloud DT + MobileNetV2; smart contracts	Expert labels	Accuracy 0.82 ± 0.04; recall 0.87 ± 0.07; AUC 0.87 ± 0.04
7	DTs for soldier musculoskeletal health. Lloyd DG et al., 2023	Narrative review	Synthesize personalised DT + AR to prevent injury	Active-duty soldiers (conceptual)	Real-time DT + wearables + AR	Conventional training	Proof-of-concept strain/ force estimation; no head-to-head data
8	Full-body illusion in anorexia nervosa. Keizer A et al., 2016	Counter-balanced crossover	Does immersive avatar reduce body-size overestimation?	30 female AN + 29 healthy controls	Synchronous stroking with 1st-person avatar	Asynchronous stroking; baseline	Abdomen misestimation 60.5 → 48.9 % ($p = .005$); hip/shoulder similar; effects 2 h 45 min
9	AR catheter navigation (radiation-free). Palumbo MC et al., 2022	Eng. validation	Develop HoloLens2 nav system	1 expert + 10 novices	EM-tracked catheter DT in AR	Fluoroscopy implicit	Reg. error 2.7 mm; no expert–novice difference
10	AR with 3-D printed marker. Moreta-Martínez R et al., 2018	Bench + single case	Auto-register CT to field via printed guide	Phantom + 1 patient	CT-derived DT in AR	None	Guide placement RMSE 1.9 mm; AR localisation 2.9 mm

Table A1: Studies applying digital-twin / metaverse technologies in health and biomedicine (2014–2025)

Id	Name and Reference	Study Design	Objective	Population	Intervention	Comparator	Outcome
11	Low-cost Wii VR stroke rehab. Tsekleves E et al., 2014	Prototype + single case	Test “ReWiiRe” rehab platform	31-y woman, 11 y post-stroke	Wii-remote VR exercises, 6 × 18 min	Baseline	FMA-UE +8; NHPT 29 → 7.8 s; MAL +3; MAS 2; 9/10 enjoyment
12	Out-of-body motor imagery after stroke. Xu et al., 2024	Within-subject EEG	Does avatar ownership boost MI ERD?	13 chronic stroke pts	E-MI (sync)	C-MI (async)	Ipsilesional ERD 20.4 % vs 11.7 % ($p = .01$); no behavioural data
13	Remote-surgery DT over 4G. Laaki H et al., 2019	Prototype usability	VR-controlled UR3 over 4G	73 volunteers	DT with haptics/video, 125 Hz loop	None	Lag < 150 ms; RMS 1 mm; 80 % adapt after practice
14	Kinect videogame for FOG in PD. Nuic D et al., 2018	18-session pilot	Feasibility/ effect on FOG	10 advanced PD	“Toap Run” Kinect	Usual care baseline	FOG-Q 39 %; 7/10 fall-free ($p = .023$); gains faded by 3 mo
15	VR pure-tone audiometry training. Kwak C et al., 2024	Within-subject compar.	Feasibility VR-PTA vs real PTA	31 audiologists	VR-PTA (Quest 2)	GSI-61 audiometer	Ease/usefulness NS (all $p > .05$)
16	OpVerse vs Synapse 3D. Zheng YA et al., 2025	Cross-over usability	Compare VR vs desktop 3-D planning	12 surgeons	OpVerse (Quest 3 streaming DT)	Synapse 3D	SUS 73.3 vs 53.8 ($p = .0006$); faster repeats in OpVerse
17	Hybrid hip energy harvester. Hao D et al., 2025	Eng. bench + treadmill	Develop HJEH + AI DT	7 healthy males	HJEH + DL classifier + Unity DT	None	357 mW; 10 000 μF→5 V in 110 s; 99.95 % accuracy; stable 100 k cycles
18	DAE-BLS disease prediction. Kulkarni C et al., 2024	Retrospective ML	DT-enabled DAE-BLS vs ML baselines	Public diabetes, HF, ECG, CT datasets	DT–DAE-BLS	LR, RF, DNN, CNN, BLS	Diabetes 94.9 % vs 72–94 %; HF 97.1 %; ECG 98.8 %; 48 % faster training
19	VR onboarding digital-twin hospital. Zackoff MW et al., 2023	Implementation study	Feasibility/ acceptance of autonomous VR onboarding	2 086 staff (1 495 completed)	Five-phase immersive DT of new unit	None	72 % completion; 86–94 % positive learning; 2 000 vs 5 000 h saved
20	ML DTs of breast cancer. Moztarzadeh O et al., 2023	Proof-of-concept ML	Build ML DTs for serum markers	64 cancer + 52 controls	LR, DT, RF, GBM models	None	R^2: 0.82–0.93; MAE 3–5 units; no clinical outcomes
21	Metrics for surgical dexterity in VR. Wu M et al., 2025	Repeated-measures VR	Validate dexterity metrics	34 surgeons	LAPMentor VR under varied configs	In-study comparisons	10× mag ↓ path length; sitting ↑ accuracy; exp 6–10 y best depth tasks
22	Exoskeleton DT kinematic accuracy. Ratschat A et al., 2023	Single-case validation	7-DOF exoskeleton DT	1 healthy male	Unity DT driven by robot	FK output; real robot	DT vs FK 18.1 ± 3.1 mm; DT vs RR 22.1 ± 3.3 mm; speed/smoothness similar
23	Korean cadaver DT for anatomy. Choi SY et al., 2025	Tech dev + pilot	Build full-body DT in HoloLens cloud	Mixed students/staff	“Skeletomy” VR/AR DT	None	100 % “positive”; themes: engagement, collab; lag noted; no learning stats

Table A2: Studies applying digital-twin / metaverse technologies in health and biomedicine (2014–2025)

Id	Name and Reference	Study Design	Objective	Population	Intervention	Comparator	Outcome
24	Decentralized SplitFed learning (DSFL). Stephanie V et al., 2024	Simulated ML exp.	DSFL links edge DTs to metaverse	Simulated 50 IoMT devices	DSFL	FedAVG IID/Non-IID; HFL	PathMNIST improper cut 10 pp; optimal DSFL > HFL/FedAVG; faster convergence
25	SurRoL v2 human-in-loop RL. Long Y et al., 2023	Simulation RL study	DT simulator + expert demos for RL	4 med + 4 eng students	Twin PSM arms + haptics	Script demos; non-expert demos	Success 89.7 ± 6.4 % vs 66.3 % vs 43.2 %; fewer steps and distance
26	Secure MDT & cyber-resilience. Zhang J, Tai Y, 2022	Pre/post prototype	MDT lung-biopsy sim + AI	Thoracic surgeons; codebases	MDT (VatsSim-XR)	Box trainer; VR/AR; Flawfinder etc.	Skill gains (all p < .05); CodeBERT precision +10 pp, recall +20 pp for bugs
27	Autonomous endoscope robot. Zinchenko K et al., 2021	Eng. simulation	Endoscope robot centered by DT segmentation	EndoVis dataset	YOLOv3 + ResNet DT; Unity VR	None	IoU 86.6 % at 30 FPS; latency 33 ms; RoA centred
28	Automated cFFR from CT. Chakshu NK et al., 2021	Diagnostic accuracy	DT CFD cFFR vs wire FFR	25 CCTA pts	Unsupervised seg + 1D/0D CFD DT	Invasive FFR	Mean cFFR 0.76 ± 0.10 vs 0.82 ± 0.08; 0 false-neg at 0.80 cut-off
29	DT OR VR reduces paediatric anxiety. Lee J et al., 2024	RCT	VR DT OR vs 2-D video	102 children 4–8 y	4-min immersive VR DT	Tablet video	mYPAS 33.3 vs 46.7 (p = .022); perfect ICC 67 % vs 47 %; induction time 305 vs 382 s (p = .002)
30	DT-based AI rehab robot. Tao K et al., 2024	Lab crossover	Develop FAP controller; test safety	8 volunteers	DT-FAP controller	Passive; active; impedance	Interaction force 18.6 N (FAP) vs 17.7 N vs 5.3 N; safer in spasm test; faster skill gain
31	DT contextual assistance for robot-training. Hagmann K et al., 2021	Pilot controlled lab	Does DT haptic assistance aid novices?	6 novices	SCOPE DT virtual fixtures	Standard teleop	Path accuracy +60 %; rotational error ↓ (p = .009); ↓ duration & workload

Table A3: Studies applying digital-twin / metaverse technologies in health and biomedicine (2014–2025)

Appendix B: Supplementary Figures

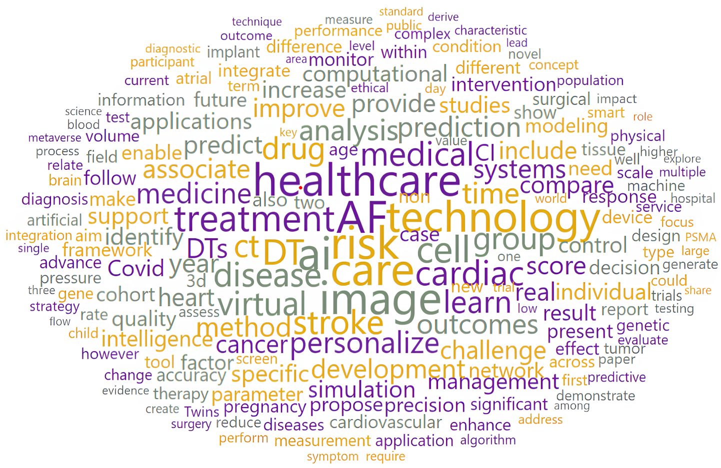

Figure B1: Bag of Words frequency distribution.

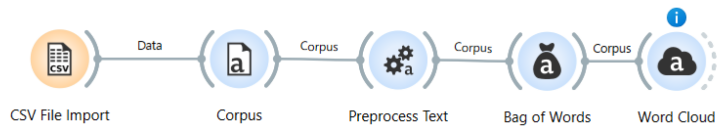

Figure B2: NLP processing pipeline.

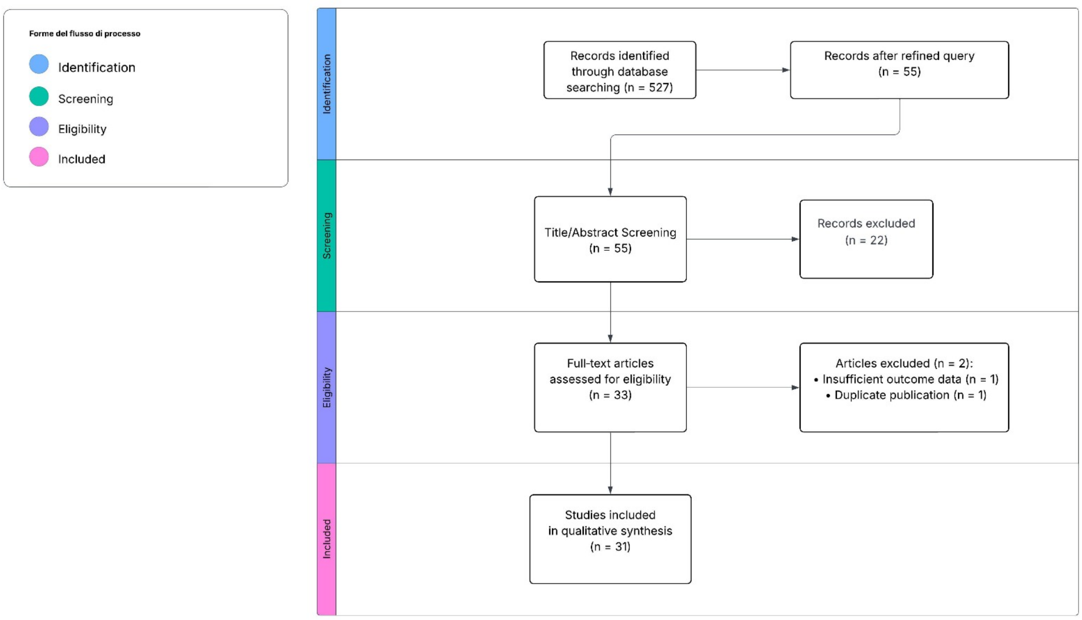

Figure B3: PRISMA flow diagram documenting the study selection process with exclusion reasons at each stage.

Appendix C: Economic Evaluation Details

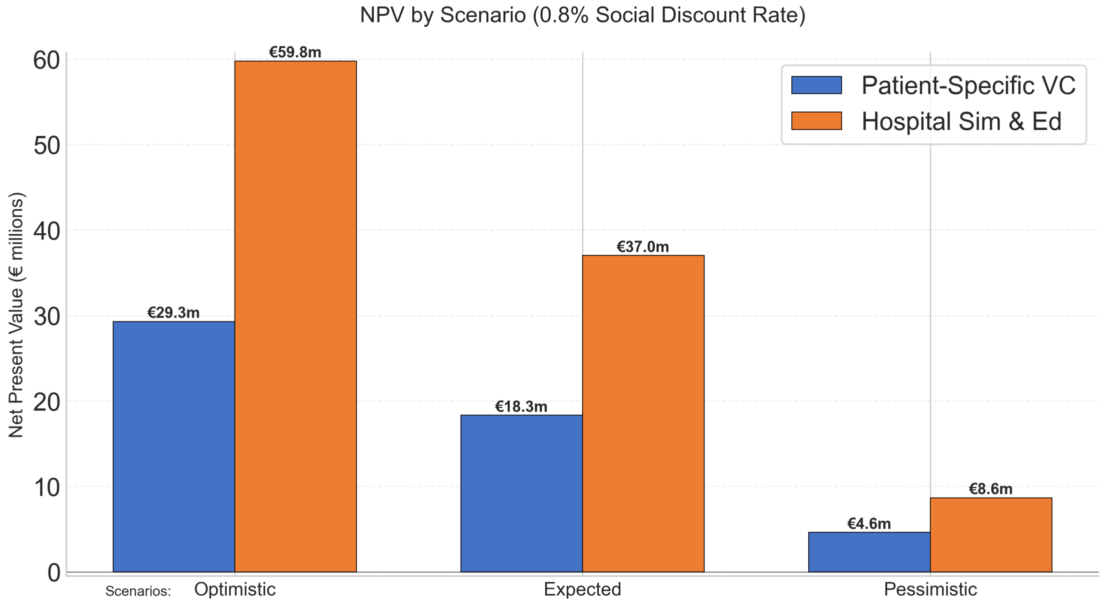

Figure C1: Net Present Value by scenario for the two macro-areas at 0.8% social discount rate.

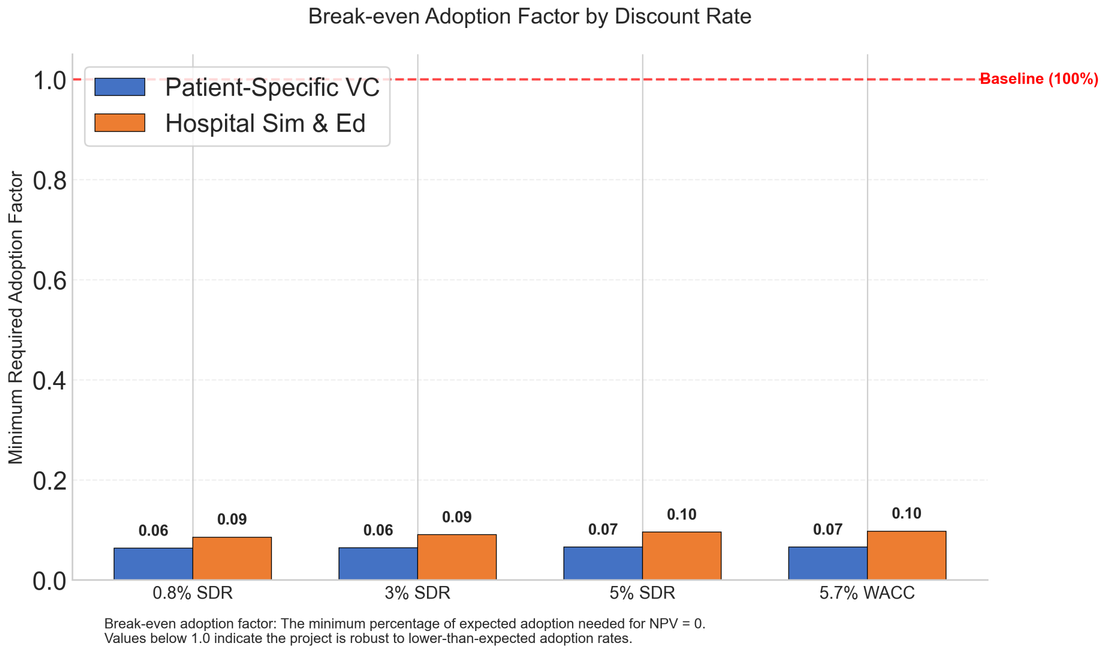

Figure C2: Break-even analysis for the investment.

Table C1: NPV Contribution Breakdown - Patient-Specific Virtual Care (MACRO1)

Factor	**Value (€M)**	**Contribution %**	**Clinical Impact**
Base Case (60% uptake, 70% compliance)	6.9	23.5%	Starting scenario value
Uptake Improvement (60% → 100%)	+11.0	37.5%	+1% €275k (€550k with multipliers)
Compliance Improvement (70% → 100%)	+5.9	20.1%	40% fewer reoperations
Hardware Cost Reduction (120% → 100%)	+0.9	3.1%	Marginal impact
Optimization Factors	+5.3	18.1%	Includes 120% uptake, 130% compliance
Total NPV	**29.3**	**100%**	BCR 15.7

Table C2: NPV Contribution Breakdown - Hospital Simulation & Education (MACRO2)

Factor	**Value (€M)**	**Contribution %**	**Key Insights**
Base Case (60% uptake, 70% compliance)	13.5	22.6%	Initial scenario value
Uptake Improvement (60% → 100%)	+11.3	18.9%	+1% uptake +€377k
Compliance Improvement (70% → 100%)	+12.2	20.4%	30% error reduction
Hardware Cost Reduction (120% → 100%)	+0.0	0.0%	No significant impact
Optimization Factors	+22.7	38.0%	Includes 120% uptake, 130% compliance
Total NPV	**59.8**	**100%**	IRR 237%