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USE OF IMMERSIVE TECHNOLOGIES FOR SUSTAINABLE BUSINESS PROCESSES: CONNECTING RESEARCH AND PRACTICE

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ABSTRACT

Immersive technologies such as virtual reality, augmented reality, mixed reality, and extended reality are increasingly discussed as a way to enable sustainable change in organizations. However, it remains unclear how these technologies support the sustainable design of primary business processes and what impact they have on sustainability. This article builds on an earlier conference paper titled "The Use of Immersive Technologies to Improve Sustainable Business Processes: A Structured Literature Review." It extends the literature review with an industrial perspective. Using a structured literature review following the methodology of vom Brocke et al. and the PRISMA guidelines, the study analyzed and categorized 15 studies by Porter's primary activities, the three dimensions of sustainability, and the types of immersive technologies. The study identifies three recurring sustainability mechanisms: resource substitution, process optimization, and capability enhancement. At the same time, it shows that standardized indicators and process-oriented frameworks are missing. To validate the results, experts from various fields and companies were interviewed. The interviews confirm the relevance of the identified mechanisms, highlight application scenarios with strong sustainability potential, and provide indicators to measure their impact. By combining research and practical perspectives, the article provides a foundation for developing measurable sustainability indicators and a process-oriented framework for the sustainable design of business processes using immersive technologies.

KEYWORDS

Sustainable Transformation and Metrics, Business Processes, Immersive Technologies, SLR, Qualitative Research

1. INTRODUCTION

Given global challenges such as climate change, scarce resources, and increasing regulatory requirements, companies across industries are under pressure to improve their sustainability performance (Petruse et al., 2016). This requires a comprehensive, sustainable transformation of their core business processes, as significant sources of resource consumption, emissions, and social impacts can be found throughout the value chain—for example, in the areas of inbound logistics, production, marketing, and service (Porter, 1985; Vacchi et al., 2021). The sustainable transformation of primary business processes has become a key challenge for companies across industries seeking to achieve ecological, economic, and social sustainability goals (Petruse et al., 2016). At the same time, immersive technologies, including augmented reality, virtual reality, mixed reality, extended reality, and metaverse environments, have experienced a second wave of interest. The technological basics for immersive technologies were already developed in the 1980s and 1990s but they remained niche applications for a long time due to high costs and limited computing power (Hofma, 2020). In the late 2010s, immersive technologies experienced a renewed wave of interest when advances in computer hardware brought faster and cheaper computing power to market and the development of consumer-friendly VR headsets increased their popularity (Cosio et al., 2023; Hofma, 2020). They enable new forms of interaction, visualization, training, monitoring, and collaboration (Garcia Fracaro et al., 2022) and are increasingly being used in operational contexts (Cao et al., 2025) such as manufacturing (Thiede et al., 2022), logistics (Pathak et al., 2025; Sadeghi et al., 2025), maintenance (Petruse et al., 2016), construction (Ertz et al., 2024; Li et al., 2024), and customer service (Achuthan et al., 2025; Rega et al., 2025). Immersive technologies can support more sustainable business processes by visualizing processes and optimizing user guidance (Porter & Heppelmann, 2017). Virtual prototyping can reduce the demand and the waste of physical resources, increase the precision of task execution, and support resource-efficient decisions. In addition, it enables more resource-efficient decisions and contributions to sustainability by improving efficiency and enhancing the design and execution of business processes.

Against this background, it is necessary to clarify what sustainable business processes are and how previous studies define them. To provide an overview of immersive technologies, sustainable transformation, and business processes, this structured literature review follows the method of vom Brocke et al. (vom Brocke et al., 2009). This study consolidates what is known about the usage of immersive technologies in the sustainable transformation of primary business processes. Despite this potential, research remains insufficient on how immersive technologies are used across business processes and what contribution they make to all three dimensions of sustainability. Previous studies often focus on individual use cases or specific technologies, leaving a lack of a comprehensive view of their relevance to sustainable business processes. To address this research gap, this study examines the current state of research on the use of immersive technologies in sustainable business processes through a structured literature review. First, the study defines its objectives and scope and formulates the research questions (RQ1–RQ3). Cooper’s taxonomy (Cooper, 1988) is used to specify the type and focus of the study. It provides an established framework for structured literature reviews and ensures methodological rigor. Porter's value chain model structures the analysis of business processes by providing a framework for evaluating primary business activities and enabling a systematic presentation of immersive technologies across process phases.

- RQ1: What are sustainable business processes and which specific fields of application for immersive technologies are described in the literature for designing sustainable business processes to realize primary activities in Porter's value chain?
- RQ2: How do immersive technology applications contribute to ecological, economic, and/or social sustainability, and what criteria and metrics exist for evaluating sustainability in business processes?
- RQ3: What research gaps exist regarding the use of immersive technologies for the sustainable design of primary activities in Porter's value chain?

RQ1 clarifies what sustainable business processes are, how previous studies define them, and provides a systematic mapping of relevant applications. RQ2 examines their contributions and indicators related to sustainability. RQ3 identifies unexplored areas and gaps in the evidence to develop a future research agenda. This study provides an overview of current research on immersive technologies in sustainable business processes, identifies patterns in the application of immersive technologies across processes and sustainability dimensions, and outlines a research agenda by highlighting key gaps and opportunities for future research.

This article is an extended version of the paper "Use of Immersive Technologies to Improve Sustainable Business Processes: A Structured Literature Review" presented at the IADIS Sustainability, Technology and Education 2026. This journal article extends the work through a more detailed analysis of the literature and expert interviews. The literature analysis includes a systematic mapping of immersive technologies to Porter's primary value chain activities, recurring sustainability mechanisms, and sustainability evaluation criteria and metrics. Expert interviews with industry practitioners complement these findings by providing practical insights into relevant application scenarios and how to measure sustainability effects. By integrating both perspectives, this article provides a more comprehensive understanding of how immersive technologies can support the sustainable design of business processes.

2. THEORETICAL BACKGROUND

2.1 Sustainability & Sustainable Transformation

Sustainability rests on three interconnected pillars: ecological, economic, and social (Linne & Schwarz, 2003). The goal is to protect natural resources, ensure long-term economic performance, and promote social justice and well-being without compromising future generations' needs (Linne & Schwarz, 2003; Winkelmann et al., 2024). The United Nations' 2030 Agenda and its 17 Sustainable Development Goals (SDGs) provide a global framework for this transformation by combining social development, economic growth, and environmental protection (Winkelmann et al., 2024). Technology is a key factor in implementing sustainability and transformation by optimizing processes and minimizing ecological impacts, for example, by promoting the circular economy and using Industry 4.0 technologies (Vacchi et al., 2021). Evaluating sustainable business processes requires clear metrics and indicators that measure ecological, economic, and social impacts and enable transparency, comparability, and continuous improvement (Pathak et al., 2025).

2.2 Business Processes

A business process is a structured set of activities that directly contributes to an organization's value creation and is carried out by people, machines, or IT systems that use resources and information in a goal-oriented manner consistent with the business strategy (Mehler-Bicher et al., 2019; Žemgulienė & Valukonis, 2018). Such processes are characterized by an end-to-end orientation that extends from the initial requirement, such as a customer order, to final fulfillment, such as delivery. Business processes operate across companies, departments, and organizational boundaries (Winkelmann et al., 2024; Žemgulienė & Valukonis, 2018). Porter's value chain provides an analytical tool that enables companies to structure their business processes along the value chain and evaluate sustainability, efficiency, and competitive advantages, divided into primary and support activities (Porter, 1985; Porter, 2007).

Primary activities directly contribute to product creation and customer value, **Figure 1**. They comprise Inbound Logistics (traceability and quality inspection of inputs), Operations (production, manufacturing, prototyping, internal logistics, maintenance, monitoring, quality control, and testing), Outbound Logistics (storage and distribution of finished goods), Marketing and Sales, and Services (post-sales activities such as customer relationship management and support). Support activities contribute indirectly to value creation by enabling the efficient execution of primary activities (Porter, 1985; Porter, 2007; Vacchi et al., 2021). These include Procurement and Supplier Management, Technology Development, Human Resource Management (recruitment and employee management/ training), and Firm Infrastructure (finance, legal affairs, and facility management).

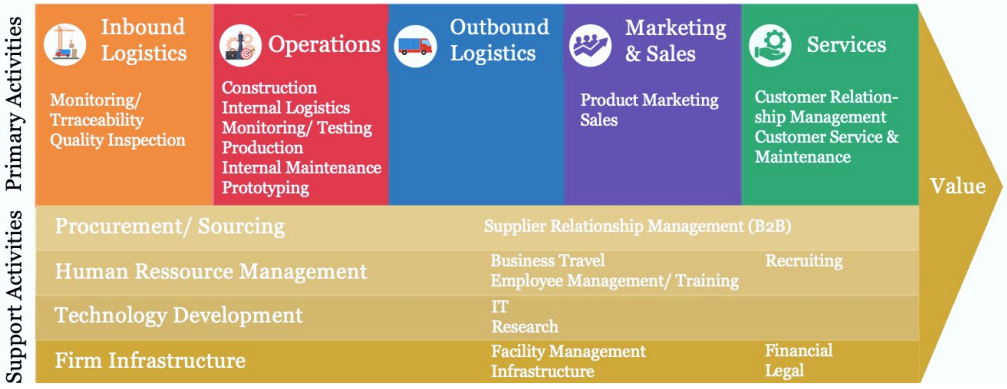


Figure 1. Porter's Value Chain (Porter, 2007)

2.3 Immersive Technologies

Immersive technologies include advanced digital systems designed to create a sense of physical presence in a virtual environment. These technologies enable innovative interactions with information and the environment by engaging the senses. The understanding of immersive technologies and their terminology has developed over time. Two classifications are Milgram & Kishino's Reality-Virtuality Continuum (RVC) (Milgram & Kishino, 1994) and Rauschnabel's XR Framework (Rauschnabel et al., 2022). The RVC describes a spectrum

ranging from a purely real environment to a purely virtual environment, showing the various forms of mixed reality (Milgram & Kishino, 1994). Rauschnabel et al. acknowledge Milgram's ideas but expand on them with more nuanced considerations for AR and VR experiences, e.g. through the concepts of “local presence” and “telepresence” (Rauschnabel et al., 2022). Because of its conceptual breadth, Milgram and Kishino's model for defining immersive technologies provides a suitable basis for further study. Based on the frameworks, the terms can be defined as follows (Milgram & Kishino, 1994; Pamparau, 2023; Rauschnabel et al., 2022): Augmented Reality (AR) enriches the real environment with real-time digital content such as text, graphics, or 3D objects. Virtual Reality (VR) replaces the real world with a fully computer-generated environment, typically accessed through head-mounted displays and controllers. Metaverse refers to interconnected virtual worlds in which users, represented by avatars, can interact. It integrates elements across the RVC, from VR environments to AR-based extensions of the physical world. Mixed Reality (MR) enables the coexistence and real-time interaction of physical and virtual objects. Extended Reality (XR) serves as an umbrella term encompassing AR, MR, and VR and is commonly used in business contexts to describe technologies that overlay physical reality. Immersive technologies are widely used and are increasingly being applied in commercial sectors such as marketing, real estate, and remote work (Petruse et al., 2016; Sneha Saju et al., 2022). In education, they promote experiential learning by enabling interactive, safe exploration of complex concepts, increasing motivation and engagement, particularly in engineering and medical education (Bano et al., 2024; Garcia Fracaro et al., 2022). In healthcare, immersive technologies facilitate advances in areas such as surgical planning and training (Sulis et al., 2019). In industry and manufacturing, they support product design, training assembly and maintenance personnel, quality control, IoT data visualization, and the implementation of digital twins and networked production systems (Bano et al., 2024; Holly et al., 2022). In culture and tourism, immersive technologies enable interactive museum experiences (Bilan et al., 2024).

3. METHODOLOGY OF THE SLR

The review follows the framework proposed by vom Brocke et al. (2009), which provides a structured, transparent approach to literature reviews through five steps and emphasizes systematically deriving a research agenda. To enhance methodological rigor, the review follows the PRISMA guidelines (Page et al., 2021). Together, these frameworks combine conceptual grounding with transparent, traceable reporting.

1. Definition of Scope: Following the recommendations of vom Brocke et al., the scope of the study is defined based on Cooper’s taxonomy (Cooper, 1988; vom Brocke et al., 2009), which comprises six categories: 1) focus, 2) goal, 3) perspective, 4) coverage, 5) organization, and (6) audience. The review focuses on research outcomes related to structured approaches to immersive technologies in a sustainable business context. Its objective is to synthesize existing literature, identify research gaps, develop a research agenda, and suggest future research directions. The paper is conceptually organized to offer an overview of structural approaches used in prior research. The paper adopts a neutral perspective to present the existing fields of application comprehensively. The target audience includes both general and specialized researchers as well as practitioners with an interest in implementing immersive technology applications. Because of the structured, multi-method search approach, the review aims to

provide representative coverage of the relevant literature.

2. Conceptualization: The second step consists of defining the key terms, finding synonyms and core concepts of the research field (vom Brocke et al., 2009). This includes a precise description of the three main aspects “sustainability and sustainable transformation”, “business processes as primary value-adding activities” according to Porter (Porter, 1985), and “immersive technologies”. The search strategy comprises three dimensions, which are combined using the Boolean operator AND. Therefore, only publications that cover all relevant subject areas are included. Sustainable Transformation (A) is captured through terms related to ecological, social, and economic transformation, including sustainability, transition, ESG, and SDGs, to identify studies addressing immersive technologies within the context of sustainability-oriented organizations. Business Processes (B) include terms related to business processes such as enterprise activities, process-oriented applications, process optimization, and efficiency across the value chain, ensuring coverage of diverse application areas, including logistics, production, manufacturing, construction, maintenance, quality management, monitoring, traceability, prototyping, marketing, sales, and customer relationship management and services. Immersive Technologies (C) include commonly used concepts such as Metaverse, Virtual, Augmented, Mixed, and Extended Reality, as well as their respective abbreviations (MR, VR, AR, XR), which jointly represent the immersive technology domain.

3. Literature Search: The third step defined inclusion and exclusion criteria to enable systematic data extraction from the selected literature (vom Brocke et al., 2009). No temporal restriction was applied, as immersive technologies represent a relatively recent research domain, with most relevant studies published after 2010 and predominantly in the 2020s. The literature review used Web of Science, EBSCOhost, and IEEE Xplore, as these databases provide a comprehensive overview of research in information systems and business administration. The distinction between the “Web of Science Core Collection” and “Web of Science All Databases” was considered to ensure both the depth and breadth of the literature review. While the "Core Collection" provides high-quality, curated sources, "all Databases" allows for broader coverage of research findings. Scopus and Google Scholar were excluded due to limitations in query processing, transparency, and reproducibility. In addition, backward and forward snowballing was applied to complement the database search. This approach helps identify relevant studies through references that keyword-based searches may not retrieve. In addition to systematic database searches, the AI-powered tool JenniAI was used in an exploratory approach to identify potentially relevant literature. However, because AI-generated search results are dynamic and not reproducible (Anthuvan et al., 2025), these tools were not considered part of the core search process. Repeated searches using the same search query may yield different results, as AI-based literature search systems can change over time. The literature was selected in two steps (**Figure 2**). Initially, titles and abstracts were reviewed, and peer-reviewed studies in English on the relevant topics were selected. Following this, the full texts of these studies were reviewed to ensure they were relevant to the research question. Studies on other digital technologies were excluded. The PRISMA diagram (**Figure 3**) illustrates the process of the literature selection.

4. Literature analysis and classification: The fourth step involves the structured analysis and classification of the identified literature. Each publication was coded using a predefined set of categories based on Schryen (Schryen et al., 2015). These categories capture the type of research contribution (research outcomes, integration, or conceptual), the adopted perspective (neutral representation), and the intended target audience (specialized scholars, general scholars, and practitioners or policymakers). Following the methodological guidance of vom Brocke et al. (vom Brocke et al., 2009), these dimensions were organized into a concept matrix that

served as an analytical framework to structure the reviewed studies. To classify the sustainability impacts of the identified studies, a coding scheme based on the triple-bottom-line concept was applied. The ecological dimension includes studies that address ecological impacts, such as reducing resource consumption, energy consumption, emissions, or material waste. The economic dimension encompasses efficiency gains, cost reductions, productivity improvements, or overall business performance. The social dimension encompasses people-related aspects such as employee well-being, the effectiveness of training programs, workplace safety, or the user experience. To prevent a study from being forced into a single category, studies that address more than one sustainability dimension are assigned to all relevant categories. The small sample size (n=15) reflects the field's emerging nature and allowed for a more detailed qualitative analysis of individual studies.

5. Development of the research agenda: The final step focuses on the derivation of a research agenda based on the results of the literature review. By analyzing the distribution of research contributions, application areas, and sustainability perspectives, the study identifies gaps in existing research. In particular, the analysis shows a lack of generalizable, structured patterns for using immersive technologies in sustainable business processes. Furthermore, no clear, uniform method exists for measuring the ecological, economic, and social impacts of immersive technologies across the primary activities of Porter's value chain. The study examines how companies are currently using immersive technologies and which technological and sustainability-related factors influence this use. This provides several approaches for further research, such as developing comprehensive models for measuring sustainability and conducting empirical studies across business processes and industries.

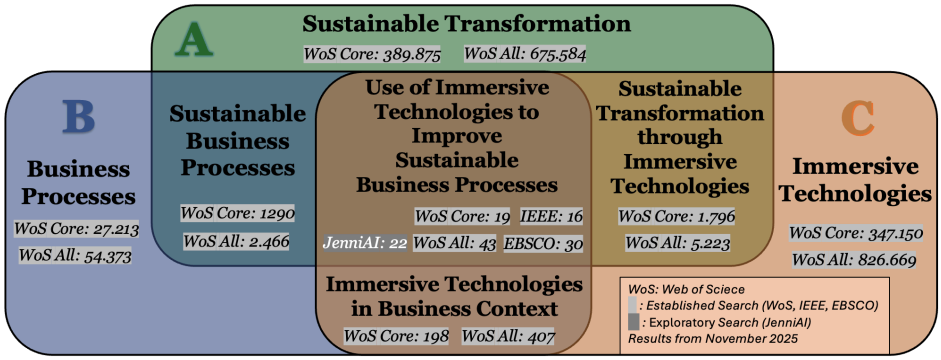


Figure 2. Documentation of the search result (Results from November 2025)

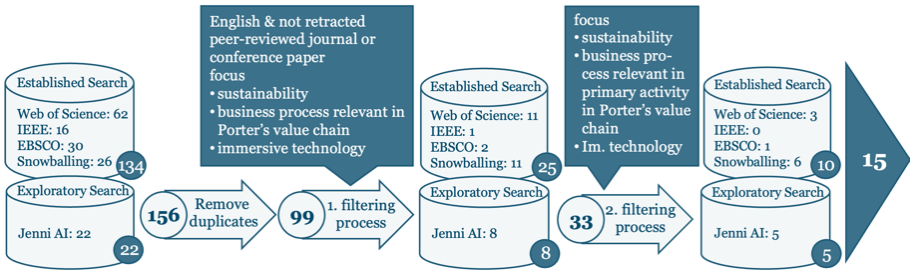
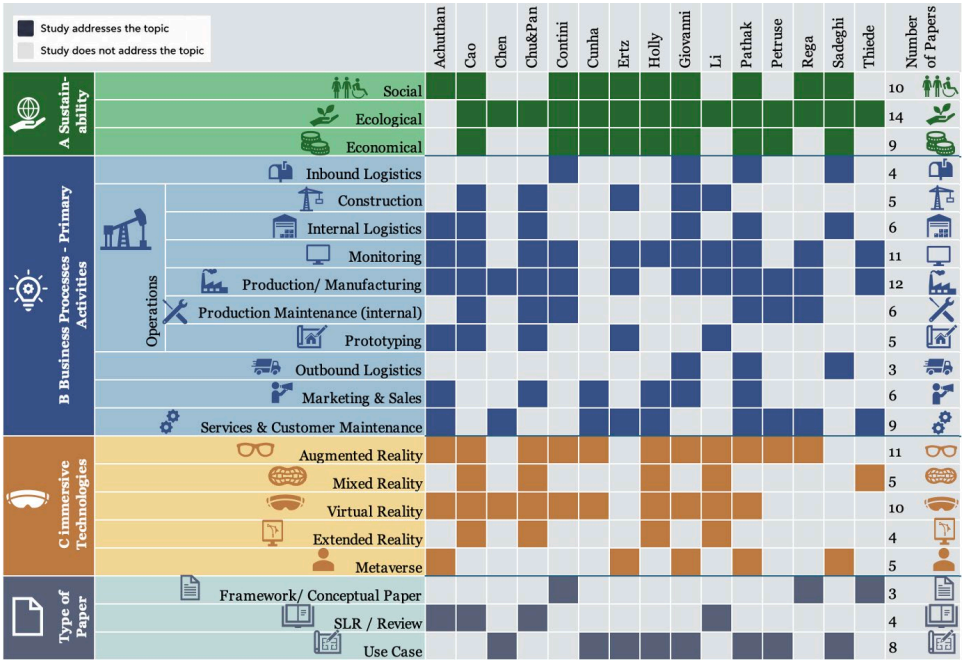


Figure 3. PRISMA Flow Diagram*Findings of the SLR*

3.1 Sustainable Business Processes

The structured literature review identified 15 studies focusing on the use of immersive technologies in sustainable business processes. The results are categorized by research question and focus on three aspects: understanding sustainable business processes, the use of immersive technologies in primary business activities, and the supporting sustainability mechanisms and indicators. To answer RQ1, this study analyzes how the literature defines sustainable business processes. Because the term is used in various ways and there is no uniform understanding, a clear definition is essential to systematically identify and compare applications of immersive technologies in this context. A sustainable business process is designed to operate over a long period without exploiting natural, social, or economic resources, while also positively impacting the environment, society, and the economy (Petruse et al., 2016). From an ecological perspective, the impact on the environment is reduced through efficient use of resources and the principles of the circular economy; from an economic perspective, it remains profitable through efficiency gains; and from a social perspective, it prioritizes employee well-being and responsible corporate governance (Cao et al., 2025; Chen et al., 2021; Chu & Pan, 2023; Contini et al., 2025). Green Design integrates these dimensions to reduce resource consumption, costs, waste, and ecological impact (Contini et al., 2025). A Sustainable Organization (Petruse et al., 2016) or Sustainable Company (Pathak et al., 2025) designs products and services that use the current environment, with one measure of success being how well a company performs when it makes products from renewable resources.

Table 1. Literature Overview and Categorization by Subject Area



In response to growing sustainability challenges, companies are adapting their strategies and business processes to align with the three pillars of sustainability (Pathak et al., 2025; Petruse et al., 2016). **Table 1** provides an overview of the areas of application for immersive technologies described in the literature, organized according to the primary activities of Porter's value chain, and thereby answers the second part of RQ1 as well as the first part of RQ2. It shows which process phases use immersive technologies to design sustainable business processes and how these applications contribute to ecological, economic, and social sustainability. This provides a basis for comparing sustainability impacts across individual process phases. The ecological dimension is addressed most frequently (14 papers), followed by social (10) and economic (9). However, fully integrated approaches remain rare (8).

Regarding business processes, the strongest concentration is in operational activities. The most addressed processes are production (12), maintenance (11), services (9), followed by internal logistics, marketing, and production maintenance (all 6). Construction, prototyping (all 5), inbound logistics (4), and outbound logistics (3) receive comparatively little attention. This indicates that existing research focuses on internal efficiency improvements, while sustainability-oriented applications in upstream and downstream value chain activities remain underexplored. Regarding immersive technologies, AR (11) and VR (10) dominate literature. MR, XR and Metaverse occur with similar frequency but less often (4-5). AR is used more frequently than other technologies because it can be integrated into existing physical work environments without fundamentally altering process structures; VR often requires fully simulated environments. In addition, the analysis identifies three frameworks that propose standards or structuring approaches for using immersive technologies in sustainable business processes (Contini et al., 2025; Rega et al., 2025; Thiede et al., 2022). However, these frameworks remain largely technology-centric and focus on selected application contexts rather than providing an integrated, cross-process perspective. In **Table 2,** the key contributions and limitations of the frameworks are summarized.

Table 2. Key Contributions and Limitations of the Frameworks

Framework	Technology	Business Process	Sustainability	Key Contribution	Key Limitation
Contini et al. (2025)	Multiple technologies (AR, VR)	Multiple processes (Logistics (Inbound), Monitoring, Production/ Manufacturing, Production Maintenance)	Tripple Bottom Line (ecological, economic, social)	Holistic approach integration of various technologies and aspects of sustainability	No process-specific guidelines
Rega et al. (2025)	Focused on AR	Multiple processes (Production/ Manufacturing, Monitoring & Maintenance, Services & Customer Maintenance)	Focused on ecological, social	Implementing AR in sustainable industrial practices	Focus on a single technology and limited value chain perspective
Thiede et al. (2022)	Focused on MR	Multiple processes (Monitoring, Production/ Manufacturing, Services & Customer Maintenance)	Focused on ecological	Design recommendations for sustainable manufacturing using MR	No integration across sustainability dimensions and processes

3.2 Sustainable Mechanisms, Indicators & Metrics

The reviewed studies identify three recurring mechanisms through which immersive technologies can contribute to sustainability: **resource substitution**, **process optimization**, and **capability enhancement**. Resource substitution refers to replacing physical resources or activities with virtual alternatives, such as physical prototypes, on-site maintenance work, or training environments, thereby reducing material consumption, waste, and travel-related emissions. Process optimization refers to improving existing business processes through real-time visualization, simulation, and context-specific guidance. AR-based instructions and real-time monitoring can reduce cognitive load, errors, and rework, leading to more efficient, consistent execution. Capability enhancement refers to using immersive environments to

improve employee skills, training, decision-making, and occupational safety. Immersive training lets employees practice hazardous activities without exposure to the corresponding physical risks. Several mechanisms may come together in a single application, and their impact on sustainability depends on the specific process changes and the measurable improvements achieved compared to the conventional process. To address the second part of RQ2, the reviewed studies identify sustainability models and metrics. Sustainability indicators are often structured along the Triple Bottom Line (Ertz et al., 2024; Holly et al., 2022; Sadeghi et al., 2025). Several studies add the 17 SDGs to assess sustainability across organizational levels, from poverty reduction to climate protection, monitored by various indicators. (Cunha, 2025; De Giovanni, 2023; Pathak et al., 2025) Contini et al. propose life cycle–oriented sustainability metrics covering economic performance (e.g., balance between profits and costs), social responsibility (e.g., workers' rights, occupational safety, accident rates, employee satisfaction), and ecological impacts (e.g., waste generation, recyclability, CO_2 emissions) to enable a holistic assessment of sustainability performance and support human-centered green design.

Building on a life cycle perspective, Chu and Pan define ecological indicators spanning design, production, use, and end-of-life phases. Cao et al. apply 212 indicators from the Sustainable Manufacturing Indicator Repository of the U.S. National Institute of Standards and Technology to evaluate sustainability across ecological (77 indicators), economic (23), social (70), performance management (30), and technological (12) dimensions (Cao et al., 2025; Joung et al., 2013). The Sustainable Value Framework conceptualizes four dimensions: pollution prevention (reducing waste and emissions in industrial activities), product stewardship (well-being of stakeholders and product life cycle management), clean technology (decarbonization technologies for a clean environment), and base-of-the-pyramid initiatives (providing support for the vulnerable) (Hart & Milstein, 2003; Pathak et al., 2025). Based on this, the sustainability indicators identified in the studies are extracted and summarized in **Table 3**. These findings show that the relevance of individual indicators depends on the specific application context.

Table 3. Papers and Sustainability Improvements Categorized by Indicators of SMIR

Category	Indicator of SMIR	Paper & Sustainability Improvement
Ecological	Water use	Contini et al., 2025: Monitoring water consumption in AR/VR dashboards
	Energy use	Cao et al., 2025: AR to visualize energy flows and identify losses
		Chu & Pan, 2023: Real-time monitoring of machines' energy consumption via AR
	Total energy consumption	Ertz et al., 2024: Metaverse simulations to optimize energy performance
		Thiede et al., 2022: Holistic analysis of energy flows across all factory subsystems
	Energy savings	Rega et al., 2025: Real-time monitoring using AR tools to promote energy efficiency
		Cunha, 2025: Energy saving in retail through virtual try-ons
	Reused / Recycled materials	Chu & Pan, 2023: XR to promote material circularity
	Material use	Li et al., 2023: Reduction of material waste through VR/ AR prototypes in construction
		Ertz et al., 2024: Reduction of material and waste through virtual design in construction
	Pollution, Greenhouse gases	Chen et al., 2021: Reduction of CO_2 emissions through the replacement of business travel
		Holly et al., 2022: Reduction of Greenhouse gases through savings on flights
Economic	Production cost	Petruse et al., 2016: Faster programming times and reduced setup costs with AR instructions
		Sadeghi et al., 2025: Increased efficiency and cost savings in logistics within the supply chain
		Li et al., 2023: Reducing construction costs through early error detection in 3D models
	Product transfer cost	Holly et al., 2022: Cost savings through the elimination of maintenance trips
		Contini et al., 2025: Monitoring transportation and packaging costs in AR dashboards
Social	Employee health & safety	Contini et al., 2025: Absenteeism due to physical stress & ergonomic risks in social KPIs
		Petruse et al., 2016: Improving workplace ergonomics by overlaying 3D models via AR
	Employee development	Rega et al., 2025: Integrated training for operators with measurement of cognitive load
		Ertz et al., 2024: Metaverse for more efficient and cost-effective training in construction
	Customer satisfaction	Cunha, 2025: Increasing purchase confidence and reducing return rates through AR/ VR
	Community, public service policy	Pathak et al., 2025: Metaverse to democratize access to education and technical knowledge
Performance	Policy and program	Contini et al., 2025: Green design principles throughout the entire product lifecycle
Tech-nological	R&D, scientific papers / High-Tech	Giovanni, 2023: Transition to Industry 5.0 through AR/ VR with consideration of the SDGs
	Success Rate	Holly et al., 2022: Improves the success rate of technology change projects
	Technological Trends	Achuthan et al., 2025: focus on technological trends

Energy-related indicators are particularly relevant in manufacturing and monitoring applications where immersive technologies visualize and optimize energy flows. Environmental pollution and greenhouse gas emissions are mostly considered in the context of reducing business travel. In applications related to virtual prototyping, simulation, and design, the focus is on material consumption and the use of recycled materials. Employee health and safety, as well as their professional development, are key factors in training and operational applications.

4. FINDINGS OF THE EXPERT INTERVIEWS

To complement the results of the structured literature review, exploratory expert interviews were conducted, **Table 4**. The goal was to evaluate the sustainability impacts discussed in the literature, to identify relevant application scenarios, and to develop initial approaches for measuring sustainability. The interviews were not designed as a separate empirical study but rather as an additional qualitative analysis. The detailed analysis included ten interviews because they were sufficiently relevant to the research questions. The experts were selected to cover a broad range of perspectives, including technology development and consulting, industrial applications, sustainability management, and occupational safety and health. Overall, the interviews show that immersive technologies are generally not perceived as sustainable. Their sustainability potential arises from changes in business processes rather than from the technology itself. Regarding ecological sustainability, participants specifically mentioned reduced travel and transportation, as well as savings in materials and waste. The ecological impact depends on the balance between avoided physical activities and technology-related energy and resource consumption. Regarding economic sustainability, the study specifically cited time and cost savings from remote maintenance, reduced travel, and avoided production downtime. The study also identified potential in training and onboarding. At the same time, the study cited investment and development costs, as well as challenges related to application use and scalability, as potential limitations. The interviews showed that economic benefits depend heavily on how well the applications integrate into existing business processes. Regarding social sustainability, the interviews identified occupational safety, preventive health care, skills development, and learning motivation as relevant aspects.

Table 4. Overview of the relevant expert interviews in anonymized form

	Organizational context	Expert profile	Experience with immersive technologies	Focus areas of the interview
E1	IT and consulting firms / industrial application context	Consulting and implementation of immersive technologies	Several years of hands-on experience	XR in training, workplace safety, remote support, and process integration
E2	Technology companies	Founder and expert in VR, MR, and industrial simulation	Many years of experience in research and practice	Virtual production planning, simulation, and process optimization
E3	Technology companies	Founder and developer of immersive enterprise applications	Several years of experience in development and application	Visualization, training, onboarding, maintenance, and scalable XR applications
E4	Large enterprises / service sector	Expert in digital strategies	Experience with digital and immersive application scenarios	Potential and limitations of immersive technologies in planning, customer experience, and operational processes
E5	Large enterprises / sustainability management	Expert in operational sustainability	Limited direct experience with immersive technologies	Potential sustainability impacts and application scenarios for XR
E6	XR service providers	Project management and implementation of XR applications	Hands-on experience with VR, AR, and 3D simulations	Virtual factory and process modeling and training
E7	Research institute in the field of occupational safety and health	Expert in occupational health and safety using immersive technologies	Many years of experience in research and practice	Workplace safety, XR applications, and effects on ergonomics
E8	Automobile manufacturer	Expert in process optimization using XR in automotive development	Many years of experience in research and practice	XR in automotive interior development
E9	Large enterprises / service sector	Expert in digital strategies	Experience with digital solutions; currently working on a problem to be solved using AR	Potential of immersive technologies in operational processes
E10	Large enterprises / health and occupational safety	Expert in occupational health and safety	Experience with tools for workplace safety in operational settings; VR as a training tool	VR in workplace safety training

Immersive training offers opportunities, as employees can practice dangerous or challenging tasks in a safe environment while avoiding the risk of real injuries. Potential limitations include motion sickness and technology acceptance issues. Another relevant finding concerns the measurability of sustainability impacts. According to the experts, such impacts are not yet systematically tracked, and attribution to a specific immersive technology remains challenging. For most indicators, the effect can be evaluated by comparing a baseline scenario without immersive technology with an intervention scenario with immersive technology, **Table 5**. Regarding ecological and economic indicators, reductions in travel emissions, material and energy consumption, process duration, costs, or production downtime can be measured. For social indicators, changes in qualifications and task performance, employee acceptance, and intrinsic motivation can be evaluated. In addition, established tools such as RULA/REBA for assessing ergonomic risks and the (Raw) NASA-TLX for measuring perceived workload can be used. Where appropriate, the results should be normalized to a defined reference value, such as per training session, process, employee, or year. The interviews provide a basis for linking immersive technologies to sustainable business processes, while highlighting the need for standardized approaches to assign sustainability effects to specific technology applications.

Table 5. Sustainability indicators and metrics, derived from the expert interviews

	Indicator	Unit	Baseline metrics (current state [B])	Intervention metrics (XR-process [I])	(Desired) effect
Ecological	CO_2 from travel	kg CO_2 / reference unit	Travel required in conventional process	Travel required with technology	B – I; reduction
	CO_2 from production	kg CO_2 / reference unit	Misproduction, rework, & unnecessary prototypes	Corresponding production losses	B – I; reduction
	Material consumption	kg / reference unit	Material required in conventional process	Material required with technology	B – I; reduction
	Waste generation	kg / reference unit	Scrap & waste from conventional process	Scrap and waste with technology	B – I; reduction
	Energy consumption	kWh / reference unit	Energy required by conventional setup	Energy required by XR setup	B – I; reduction
	Hazardous substance use	kg or L / reference unit	Hazardous substances used in conventional process	Hazardous substances used/ substituted	B – I; reduction
Economic	Travel costs	€ / reference unit	Conventional travel & personnel costs	Corresponding costs with technology	B – I; reduction
	Maintenance costs	€ / reference unit	Current maintenance costs	Corresponding costs with technology	B – I; reduction
	Process duration	min / process	Conventional process/cycle time	Technology-supported process/cycle time	B – I; reduction
	Licensing costs	€ / user / year	Existing licensing costs, if applicable	Technology licensing costs	B – I; reduction
	Capital expenditures	€	–	Hardware, software, & development costs	I; lower investment
	Production downtime	h / year; € / year	Downtime & associated costs in conventional process	Downtime & associated costs with technology	B – I; reduction
Social	Training and qualification	% / score	Knowledge & task performance in conventional training	Knowledge & task performance in XR training	I – B; improvement
	Employee acceptance	Mean score	Acceptance of conventional process/setup	Acceptance of XR process/setup	I – B; increase
	Workplace safety	incidents / 100,000 h	Accident, incident & near-miss frequency in conventional process	Corresponding frequency with technology	B – I; reduction
	Ergonomics	RULA / REBA score	Ergonomic risk during conventional process	Ergonomic risk during XR-process	B – I; reduction
	Employee health	sick days/ employee/ year	Sick/absence days during conventional process	Sick/absence days with technology	B – I; reduction
	Intrinsic motivation	IMI interest score	Interest/enjoyment during conventional task/training	Interest/enjoyment during XR task/ training	I – B; increase
	Perceived workload	(Raw) NASA-TLX score	Perceived workload during conventional task	Perceived workload during XR task	B – I; reduction

5. RESEARCH GAPS

This section addresses the second part of RQ3 and examines gaps in existing research on using immersive technologies for the sustainable design of primary activities in Porter's value chain. Previous studies focused on individual use cases and covered only a limited number of combinations of business processes, technologies, and sustainability goals, **Table 1.** A complete analysis that links various value-chain activities, immersive technologies, and all sustainability dimensions is missing. The central research gap lies in developing process-oriented frameworks and patterns for using immersive technologies as part of a sustainable transformation. Such models could help to analyze, redesign, and compare existing applications, **Table 6.**

Table 6. Cross-Dimensional Research Gaps in Literature

A Sustainability	B Business Processes	C Immersive Technologies
The literature focuses heavily on environmental aspects (e.g., resource efficiency, emissions, energy)	The literature has a limited cross-process consideration and a strong focus on operations (monitoring (11), production/ manufacturing (12), services & customer maintenance (9), general logistics (internal/ inbound/ outbound; 7))	The literature has a clear dominance of augmented reality (11) and virtual reality (10), no paper discuss all immersive technologies
Sustainability is usually viewed one-dimensionally --> an integrated triple bottom line perspective is rarely implemented (8 papers; (Cao et al., 2025; Contini et al., 2025; Cunha, 2025; De Giovanni, 2023; Ertz et al., 2024; Holly et al., 2022; Pathak et al., 2025; Sadeghi et al., 2025))	No paper considers the use of immersive technologies along the entire Porter's value chain (3 papers cover 7–8 of 10 primary activities; (Chu & Pan, 2023; De Giovanni, 2023; Pathak et al., 2025), 2 papers cover all operations; (Cao et al., 2025; Chu & Pan, 2023)) --> focus on isolated application scenarios within primary business processes	Applications often designed to be technology-driven rather than cross-technology --> focus mostly on individual technologies, not on systematic comparisons or integrated consideration
No standardized measurement models that capture all three dimensions of sustainability together	No standardized framework or systematic study that examines the use of immersive technologies holistically across all primary activities of Porter's value chain	No study that systematically covers the range of immersive technologies in sustainable business process context

6. DISCUSSION & RESEARCH AGENDA

The literature review shows that many studies already examine immersive technologies and their significance for sustainable business processes. Previous studies mainly focused on individual applications (e.g., training, monitoring, or design) or on specific industries (e.g., manufacturing and construction). This is because researchers often examine immersive technologies in specific use cases before considering broader applications. At the same time, no standardized definitions exist for immersive technologies and related terms, which are used differently depending on the field of study. Technical research typically defines immersive technologies based on system characteristics, while business-oriented studies focus on specific use cases. Sustainability is often addressed in isolated sub-areas, which makes it difficult to compare studies and integrate the three dimensions of sustainability. This may be due to differences in measurability, as economic impacts are generally easier to quantify than ecological and social impacts.

The expert interviews also show that, despite the existence of indicators, social sustainability depends heavily on the specific context. Empirical studies suggest that immersive technologies support sustainable change in various process areas. Virtual models and simulations enable early analysis and optimization of products and processes, helping reduce resource consumption, development time, and error risk. AR, for example, supports maintenance processes by providing the required information, reducing downtime and increasing efficiency and safety. In production and logistics, immersive technologies contribute to more efficient monitoring, maintenance, and control, and help reduce resource consumption. Furthermore, immersive employee training can help to improve learning processes and promote sustainable behavior. The experts confirmed these applications but also pointed out that immersive technologies are not inherently sustainable. Instead, their contribution depends on the specific changes they enable within a business process. The expert interviews provide practical insights but are limited by the number and composition of experts and should not be interpreted as representative empirical evidence.

In conclusion, **Table 7** consolidates sustainability indicators based on the reviewed studies and interviews. The findings indicate that sustainability effects arise through three recurring mechanisms: resource substitution, process optimization, and capability enhancement. These mechanisms provide a basis for translating immersive technology use into

sustainability-oriented process changes. The identified sustainability mechanisms and indicators provide an initial basis for pattern-based research by linking process changes to measurable sustainability effects and connecting them to sustainability goals, business process problems, and suitable immersive technology configurations. Companies should prioritize process stages with high resource consumption, error sensitivity, or training intensity, particularly in production, maintenance, and training. Future research should examine measurable sustainability outcomes through long-term and cross-company studies rather than focusing primarily on feasibility and efficiency. The analysis is limited to selected databases and specific search terms related to immersive technologies, sustainable transformation, and business processes. Relevant studies that use alternative terms or were published in other databases may therefore have been excluded.

Table 7. Consolidated indicators and measurements from SLR and expert interviews (ExIn)

	Sustainability indicator	SLR	ExIn	Operationalization
Ecological	Travel-related emissions	✓	✓	Avoided travel distance × emission factor
	Production emissions	✓	–	Avoided emissions from misproduction, rework & prototyping
	Material & waste	✓	✓	Avoided material & waste quantity
	Energy	✓	✓	Technology-related energy consumption vs. avoided energy use
	Water	✓	–	Water consumption / savings
	Hazardous substances	–	✓	Amount of substituted substances
Economic	Production, maintenance & process costs	✓	✓	Avoided (miss-) production, rework, process & maintenance costs
	Process duration	✓	✓	Time required / time saved
	Travel costs	✓	✓	Avoided travel costs
	Transportation & packaging costs	✓	–	Transportation & packaging costs
	Investment & licensing costs	✓	✓	Hardware, development, & licensing costs
	Production downtime	✓	✓	Avoided downtime & production losses
Social	Workplace safety	✓	✓	Safety indicators / incidents
	Ergonomics & employee health	✓	✓	RULA/REBA; absence days
	Training & qualification	✓	✓	Learning & task performance
	Cognitive & perceived workload	✓	✓	Established workload instruments
	Acceptance & motivation	✓	✓	Acceptance & motivation scales
	Customer satisfaction	✓	–	Purchase confidence / return rates
	Access to education & knowledge	✓	–	Reach & access to training/knowledge

7. CONCLUSION

Building on the potential of augmented reality described by Porter and Heppelmann (Porter & Heppelmann, 2017), this study demonstrates that immersive technologies can support more sustainable business processes. By integrating digital information into physical environments, these technologies enhance visualization, guidance, and interaction, improving task execution and decision-making. Virtual simulations and training programs can help reduce resource consumption and CO_2 emissions. However, sustainability does not result from the technology itself, but from the process optimizations it enables. The literature review also shows that previous research has focused mainly on operational activities such as production, monitoring, maintenance, and training. Other areas, particularly up- and downstream processes as well as supply chain activities, have received much less attention. Furthermore, previous research

focuses on ecological sustainability, while social and economic dimensions receive less attention. From a technological perspective, studies focus mainly on augmented reality and virtual reality, while mixed reality, extended reality, and metaverse-based approaches receive less attention. The literature focuses mainly on isolated, technology-centered case studies, which makes it difficult to link business processes, sustainability dimensions, and immersive technologies in an integrated way. The expert interviews confirm this finding and provide additional insights into the practical application of immersive technologies and the measurement of sustainability impacts. The findings highlight that immersive technologies contribute to sustainability mainly through process-level mechanisms, including simulation, real-time guidance, and enhanced decision-making, rather than through direct sustainability interventions. Overall, the studies identify three effects: resource substitution, process optimization, and capability enhancement. Linking these mechanisms to sustainability indicators provides a basis for evaluating whether an application produces measurable ecological, economic, or social improvements. Future research should systematically document the use of immersive technologies in primary business processes and evaluate their measurable contribution to ecological, economic, and social sustainability. This study shows that immersive technologies can support sustainable change in primary value-creation processes when their technological capabilities are integrated with business processes and sustainability goals.

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