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IMMERSIVE REALITIES IN SUPPLY CHAIN MANAGEMENT: A TECHNOLOGICAL PERSPECTIVE

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Purpose: The research aims to explore the integration of immersive reality technologies into supply chain management. The study focuses on how these technologies can revolutionize decision-making processes and enhance resource optimization, leading to a more sustainable and efficient operational framework.
Design/methodology/approach: The objectives of the research are achieved through a systematic literature mapping methodology. This method involves conducting a comprehensive review of existing resources in the field of immersive realities in supply chain management.
Findings: The analysis of patent applications revealed thematic groups within the patent content and highlighted changes in the number of patents filed and granted over time. This analysis suggested that technologies implementing immersive reality are at a mature stage of the innovation process, indicating a potential intensification of activities related to the diffusion of these solutions in practice.
Research limitations/implications: The paper highlights the need for research into the long-term health effects of these technologies to ensure user safety and comfort, improve accessibility for people with disabilities, and support inclusivity. The paper also identifies limitations in the current research process, such as the lack of coordination in research efforts and technical knowledge gaps, which pose significant barriers to the successful implementation of these technologies.
Practical implications: The integration of these technologies with artificial intelligence (AI) and other advanced technologies can further enhance operational management and training, focusing on areas such as product design, quality control, and remote collaboration.
Social implications: These technologies can enhance the efficiency of supply chains, leading to reduced resource consumption and waste, which aligns with broader societal goals of sustainability and environmental conservation.
Originality/value: The paper provides a comprehensive analysis of patent applications to understand the development and application of these technologies in the field. This approach offers new insights into the thematic groups of patent content and tracks changes in the number of patents filed and granted over time, highlighting trends and the maturity of these technologies in the innovation process. The paper is primarily addressed to researchers and practitioners in the fields of supply chain management and immersive technologies. It is also valuable for policymakers and industry leaders interested in the adoption of innovative technologies to enhance sustainability and efficiency in supply chains.

Keywords: immersive realities, virtual reality (VR), augmented reality (AR), mixed reality (MR), supply chain management.
Category of the paper: Research paper, Literature review.

1. Introduction

The integration of virtual, mixed and augmented reality technologies into supply chain management has the potential to transform operational practices within organisations. By leveraging these technologies, organisations can achieve greater visibility, improved operational efficiency and enhanced decision-making capabilities.

Immersive realities, including technologies such as virtual reality (VR), augmented reality (AR) and mixed reality (MR), are relevant to supply chain management because of their potential benefits in various aspects of the supply chain process (Wenzel et al., 2003). For example, these technologies can be used in the quality control phase of products to detect defects and improve the accuracy of inspections; in training and coaching operators to improve their skills in repairing or assembling components; they can facilitate remote collaboration, image and video sharing, enabling effective communication and decision-making among supply chain stakeholders; have the potential to improve product quality, operational efficiency, collaboration and decision-making in supply chain management (Chu, Pan, 2023).

Technologies that introduce immersive realities include the use of head-mounted displays and various other devices designed to provide users with deeply interactive and immersive encounter (Somrak, Guna, 2018; Tubis, Rohman, 2023). Immersive realities allow users to perceive and engage with digital content in a way that simulates integration with their physical surroundings, blurring the distinction between the tangible world and the digitally produced realm. These technologies are used in a variety of areas, including training, simulation, visualisation, collaboration and data analysis.

The term “immersive” is commonly used in many disciplines such as education, entertainment, healthcare, and marketing. Depending on the intention, it can be understood as “surrounding” or “engaging”. The concept of immersion can be understood in both technological and psychological terms. Technologically, immersion is impacted by variables such as display resolution and frame rate that relate to the user’s level of immersion. Psychologically, immersion represents a subjective state in which users experience a sense of detachment from the physical, real world (Wong, Lee, 2024).

Immersive realities are mainly associated with virtual reality (VR), a fully computer-generated reality that is not entirely non-physical, although sometimes inappropriately. Access to it involves interaction through sensory stimuli such as visual and sound elements (Liberatore, Wagner, 2021). It aims to create a sense of presence and immersion by simulating a realistic and interactive environment, but still requires physical devices such as headsets, visualisation devices and controllers. While the environment is computer-generated, the user's physical presence and interaction within it is real (Bal et al., 2023).

Immersive reality is particularly relevant today as technological advances have made it more accessible and affordable to a wider range of industries and applications. The COVID-19 pandemic has also accelerated the adoption of these technologies, providing tools for remote collaboration and training. Its importance lies in its ability to transform industries and provide innovative solutions to cross-industry challenges (Tiwari et al., 2023; Yadav et al., 2023).

The literature mapping methodology used in this paper involves conducting a systematic review of existing resources in a particular research area in order to gain a comprehensive insight into the structure of the field, relevant topics and research trends. It is a specific form of a systematic review of sources that examines the broader topic and classifies the basic research outputs in the field under study (Chen, 2017; Waltman et al., 2010). Mapping helps researchers understand the development of a field, identify research areas, reveal the evolution of research directions, and map changing paradigms. In this paper, the development of the direction of immersive reality used in supply chain management was studied by examining active patent applications (Donthu et al., 2021). Methods and tools typically used for the analysis of bibliographic sources can be applied to the analysis of patent applications, thanks to which new insights will be developed on subject groups of the patent application content and changes in the number of patents filed and granted.

The research results may be of interest to decision makers in companies and organisations involved in supply chain operations, logistics and inventory management. The results may provide insight into how immersive reality technologies, such as virtual reality, augmented reality and mixed reality, can be used to improve efficiency, accuracy and decision-making in supply chain processes. In addition, the results may be of value to researchers investigating innovative technological solutions applied to supply chain management. The results will facilitate an understanding of how immersive realities can be used to improve supply chain management processes from a technological perspective.

This study aims to reinterpret the existing research findings on the introduction and impact of technologies using virtual, mixed or augmented reality in supply chain management, identify knowledge gaps, determine limitations and propose potential directions for future research.

2. Research background

In spaces where reality and virtuality intersect, VR refers to activities that use visual and immersive tools to create a virtual environment, so that users can experience stimuli that are as real as possible (Milgram, Colquhoun, 1999). However, its ability to provide adequate realism is limited by hardware constraints. On the other hand, AR integrates virtual images with images from the real world. The placement of virtually generated models in the real world space can enrich the final effect and thus meet the user's perceptual expectations. The division between VR and AR is based on whether visual impressions from the real world are used, regardless of the establishment of immersion or display mechanisms. When a mix of reality and virtuality is used, such technology can always be referred to collectively as the Mixed Reality (MR). However, MR more often refers to a reality that not only mixes the sensation of real and virtual reality, but also provides opportunities to interact with and access information about elements of the perceived reality (Li et al., 2018).

Virtual reality (VR) can be perceived as a gateway to a computerised world that is different from the real world (Radhika et al., 2023). Devices (headsets, goggles or rooms with screens) are used to make it feel like a different place, allowing you to move around and interact with the generated world. Augmented reality (AR) is a technology that adds digital images or information to the world around us. Mixed reality (MR) resembles a blend of the real world and the digital world, where you can see and interact with both at the same time, as opposed to AR, which superimposes digital information on the real world, but without the ability to interact between the two. MR combines elements of Augmented Reality (AR) and Virtual Reality (VR) to create a new kind of environment where real and computer-generated objects can coexist. MR is a unique way to explore and understand how real and virtual things can work together (Radhika et al., 2023).

A broader view of immersive realities has been proposed by Schnabel et al. (2007), who, in addition to VR, AR and MR, have also proposed augmented reality, mediated reality, augmented virtuality and virtualised reality (Figure 1). Amplified reality is the enhancement of the perceived properties of a physical object through the use of embedded computing resources. Amplified Reality was originally introduced as a complementary concept to AR, where AR refers to how the user perceives reality, while Amplified Reality is based on how the perceiver can control the way in which information is made available. Mediated Reality refers to a more general framework for artificially modifying human perception through devices. Mediated Reality has proven useful in deliberately reducing the perception of reality, leading to a different concept of 'reality'. It creates special effects to help urban planners visualise the resulting landscape where a building is proposed, removed or replaced from the original landscape. In the person-to-person interaction, Augmented Virtuality (AV), or the augmentation of a virtual environment with real objects, enables a multi-layered, three-dimensional virtual environment to be combined with a real-world experience. Virtualised Reality virtualises scenes from the real world and then processes them from any point of view. To generate data for such a medium, the scene must be captured by multiple cameras positioned to cover the scene from all sides.

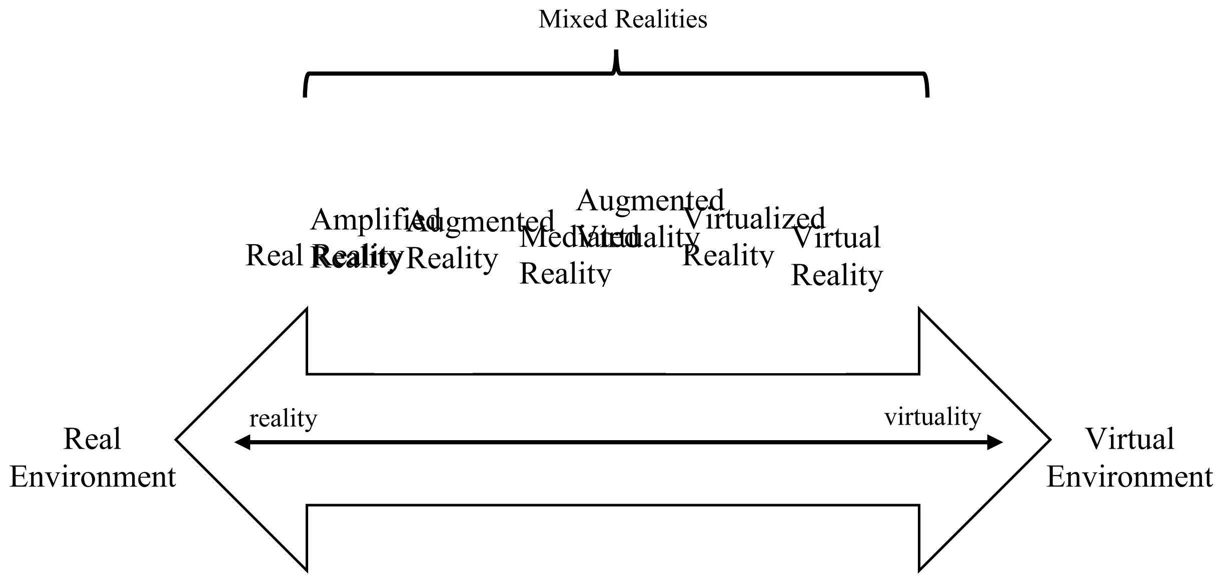

Figure 1. Order of reality concepts in the reality-virtuality continuum.

Source: modified from Milgram, Colquhoun, 1999; Schnabel et al., 2007.

A fuller understanding of concepts related to the interpenetration of reality and virtuality is aided by the analysis along two dimensions: action and perception, and the degree of interaction with real objects (Figure 2). Improving the performance of tasks performed with immersive realities requires physical interaction and feedback, which should take place in the same space. On the other hand, the development of thought and cognitive activity requires social interaction and exchange with the physical environment. The physical environment remains important because it is used to externalise thoughts and as an external memory. In this context, the degree of interaction with real artefacts refers to the extent to which users can make changes to real artefacts.

The degree of immersion is a matter of convention to some extent – whether the reality is augmented (AR) or virtual (VR) may depend on the intent and purpose of a particular application. As Sarkar et al. (2023) point out, VR can be semi-immersive, meaning that it combines elements of the real and digital worlds, allowing users to interact with the virtual environment while remaining aware of their real surroundings. This type of VR is less complex than full immersion systems and is often used for purposes such as pilot training using simulators. Users experience a virtual world through large screens or projection systems that display a simulated environment, and can interact using controls or motion platforms.

Another concept of taxonomies relating to reality spaces without reference to immersion-related "surrounding" or "engaging" is proposed by the concept of cross-realities, linking sensor networks and virtual worlds so as to enhance human interaction and perception beyond traditional boundaries (Paradiso, Landay, 2009; Yadav et al., 2023). Regardless of the accepted way of classifying the realities that make up the perceived spaces, it is suggested that as technology becomes more efficient and cheaper, we may soon see a world in which virtual and 'real' experiences are seamlessly connected and intermingle without a clear boundary.

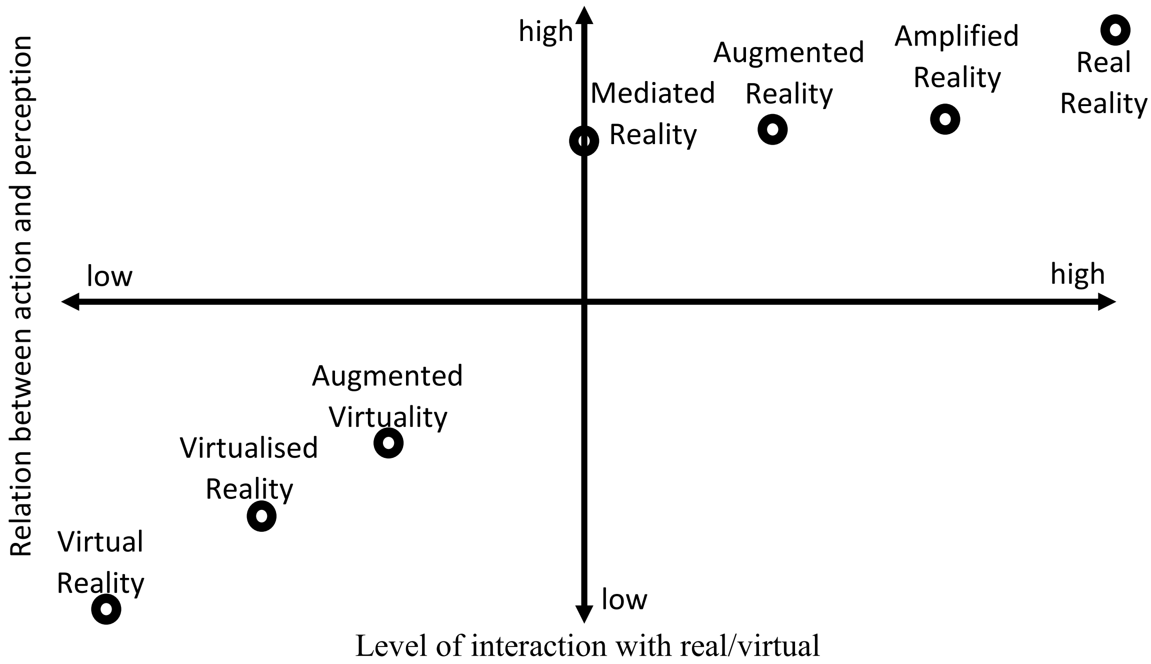

Figure 2. Immersive reality perception and influence.

Source: modified from Schnabel et al., 2007.

Virtual reality research began in the 1960s, and the results were first used commercially in the late 1980s (Cipresso et al., 2018). Augmented reality technologies are newer than VR, with the use of AR beginning in the early 1990s. Both VR and AR have developed into many applications, such as video games and learning. Four phases of VR research can be identified:

- **Pioneering** – began with the conceptualisation of VR in the 1960s and included the development of interfaces for various applications,
- **Technological development** – supported by technological advances coinciding with the "dot-com bubble" of the late 1990s, with significant investment in information technology.
- **Clinical** – began with the new millennium, focusing on applications in rehabilitation and neurosurgery, as well as improving therapeutic and laparoscopic skills,
- **Current** – growth in hardware innovation and software advances driven by independent developers and communities.

At present, VR and AR are not just about viewing realistic images, but also about interacting with the virtual world. Key application areas for VR include gaming, education and medical applications – rehabilitation and neurology. The leading countries in the field of VR research are: the United States, China, the United Kingdom and Germany (Cipresso et al., 2018). Liberatore & Wagner (2021) conducted a detailed analysis of healthcare, business and marketing research to show how immersive technologies are impacting areas such as cognitive therapy, addiction treatment and brand awareness. They showed that some technologies may be more appropriate for certain types of problems, suggesting the need for further research to match technologies to the expected outcomes.

Education is one of the obvious applications of immersive reality. VR has the potential to increase the effectiveness of higher education in areas such as (Radianti et al., 2020): engineering, computer science, architecture, surgery, nursing, learning of specific subjects – astronomy, geography, physics, security, and foreign languages. The use of learning theory is often overlooked in the development of VR applications for education, which is the key to guiding the development of tools with the realisation of learning outcomes in mind. This means that while apps may be engaging or look good, they may not be as helpful to learning as they could be if they were designed with educational principles in mind. In most cases, VR apps are evaluated based on their ease of use, rather than an actual and real assessment of their impact on improving learning outcomes. VR can make learning fun by turning lessons into games where students can earn points and badges, making them want to learn more. Tang et al. (2020) conducted research on the effectiveness of MR technology in the teaching of design-related subjects. They pointed to improved creativity and systematicity in design – MR led to better performance in the geometric analysis and model visualisation. MR allows students to interact with 3D models in real time, providing a more engaging and immersive learning experience that can stimulate creative thinking. Students who used MR technology showed significant improvements in their ability to analyse geometric shapes and creativity compared to those who had access to traditional teaching materials.

Immersive realities are also being used in very specialised areas of education. Hořejší (2015) explored the use of AR in teaching assembly tasks to workers, using a webcam and appropriate monitor configuration to overlay 3D model instructions on a real work area. Such a system can significantly reduce the time needed to learn assembly tasks. Satisfactory results for new workers have been observed after only 10 trials. The system uses simple equipment such as a webcam and monitor, making it a cost-effective solution for virtual training in assembly tasks. VR is also being used in military training (Liaropoulos, 2023). It is used to create realistic training situations in which soldiers can practice without real danger, helping them prepare for real combat situations. It allows soldiers to train in a variety of environments and scenarios to improve their skills and prepare for the different challenges they may face. VR training includes learning how to safely operate complex machinery or equipment before using it in real missions, reducing the risk of very costly mistakes during real operations.

Bhavadharini et al. (2023) explored virtual reality, augmented reality and mixed reality technologies used to understand consumer behaviour when choosing food products. They used these technologies to investigate the influence of the environment on beverage choice, demonstrating that context can influence consumer preferences. Understanding consumer behaviour is particularly important when developing new products – it helps to understand the emotions involved in the product choice. They found that immersive realities can effectively analyse consumer behaviour in food choice, which is crucial for product development and market success. Immersive technologies can provide realistic experiences, leading to more reliable data on consumer behaviour compared to traditional methods. The potential of immersive reality, particularly AR, in its ability to understand consumer behaviour, has contributed to the development of the 4C model (Rauschnabel et al., 2024). The 4C framework model includes: consumer, content, context and computing device. An effective analysis of AR usage should be based on analysing the relationship between these four elements.

Technologies such as mixed reality can improve public participation in urban land use planning by helping residents visualise plans more accurately (Büscher, Lorenz, 2023). They can make it easier for residents to understand urban planning by allowing them to view 3D models of planning spaces using mixed reality implementation devices. The limitations of this technology – its cost and limitations in the level of detail of the models obtained – have also been highlighted.

Fross et al. (2022) presented research on the use of Mixed Reality (MR) technology in research, education and architectural and building design, focusing on the presentation of BIM models and building inspections. MR can help clients and future users better understand and interact with projects, potentially reducing errors. This gives the technology the potential to replace traditional construction tools with digital, electronic and laser devices. They also showed that MR has not been widely used yet, mainly due to high costs and technological barriers. The use of VR technology can increase safety on construction sites by helping workers see and understand hazards before they occur (Li et al., 2018). Immersive realities can be used to improve safety in three areas: 1) improving safety design, 2) studying human behaviour after a disaster, and 3) emergency response training (Radhika et al., 2023). AR and VR technologies were shown as being promising for disaster management. It was suggested that future research should focus on comparing different AR and VR hardware configurations to determine their effectiveness in disaster management.

MR technology is being increasingly used in the medical field, particularly for the visualisation of 3D medical images to aid in surgical planning, diagnosis and medical training (Skalski et al., 2020). The technology allows for a more intuitive understanding of complex medical data, potentially leading to faster and more effective diagnoses. MR has been shown to improve the planning and execution of medical procedures, particularly in the minimally invasive surgery.

Interesting results have been obtained by combining technologies such as artificial intelligence (AI), artificial life (AL) and virtual reality (VR) (Chadha et al., 2023). Such a combination could create new ways of perceiving and performing tasks that could change many components of life, such as the way we travel, educate or receive healthcare. The integration of AI and VR has shown promise in improving healthcare, particularly for chronic diseases such as cancer and cardiovascular disease, allowing for more personalised treatment plans (Yadav et al., 2023). It is possible to personalise the treatment of chronic diseases and help during health crises such as the COVID-19 pandemic. However, the concerns of healthcare professionals and patients about artificial intelligence need to be addressed. Sharma & Chamoli (2023) explored solutions using VR and deep learning (DL) models in diagnosis and decision making, particularly in the context of brain tumour classification. They found that the integration of artificial intelligence with VR will increase, enabling immersive and interactive solutions for medical training and patient care. The enhanced 5G technology will improve the performance of AI and VR applications, enabling faster data transmission and reliable connectivity. The development of DL models (e.g. convolutional neural networks) will enable more accurate and efficient disease diagnosis, such as identifying brain tumours from CT images. The integration of immersive realities with other technological solutions can provide potential savings by increasing the level of healthcare services.

3. Methods and material

Literature mapping belongs to a group of methods known as systematic literature reviews (Cai, Lo, 2020). It is a specific form of systematic literature review that aims to review a broader topic, classify primary research in a particular area and identify subtopics, empirical methods used and areas of relevant empirical studies for more detailed systematic reviews.

Alternative methods to literature mapping include scoping reviews, rapid reviews and umbrella reviews. Scoping reviews provide a broad overview of a research topic, identifying key concepts, sources and gaps in the literature. Rapid reviews are designed to speed up the review process with streamlined methods, such as limiting the scope of the search or excluding certain research designs. Umbrella reviews synthesise the results of multiple systematic reviews to provide a comprehensive summary of the evidence on a particular topic (Cai, Lo, 2020). In addition to a classic literature review, extended bibliometric analysis methods are used, such as a unified science mapping approach that includes clustering and visualisation of source documents (Donthu et al., 2021).

The bibliometric analysis is a rigorous method for examining and analysing large amounts of scientific data (Donthu et al., 2021). It can be used to unravel and map complex, cumulative scientific knowledge, identify knowledge gaps, or generate new research ideas. The bibliometric analysis uses both objective (e.g., performance analysis) and subjective (e.g., thematic analysis) assessments and can be used to provide an overview of the field, identify trends, and examine patterns of collaboration. The main methods of the bibliometric analysis are performance analysis and science mapping (Figure 3).

Science mapping includes techniques such as the citation analysis, co-citation analysis, co-citation network analysis, co-occurring word analysis and co-authorship analysis. These techniques, combined with the network analysis, help show the bibliometric and intellectual structure of the research field. The performance analysis consists of analysing measures such as the number of publications, annual number of citations, citations per publication and h-index. These measures provide tools for analysing productivity and the impact of the dataset studied on the development of a specific scientific field.

The performance analysis is another category of the bibliometric analysis that focuses on examining the contribution of research components to a field. It includes the analysis of performance at different levels of the production of scientific output, such as authors, institutions, countries and journals. The performance analysis is descriptive in nature and is used to provide a background or profile of actors. It helps understand the impact of individual research actors, identify potential collaborators and assess their productivity and the quality of their outputs. The performance analysis provides a valuable insight into the current state of the research field, highlighting key players and their contributions. It can be used to identify emerging trends and knowledge gaps (Donthu et al., 2021). The above techniques, combined with the social network analysis, provide access to the intellectual structure, knowledge flows and subject cluster analysis capabilities. They help identify influential publications, key research areas, emerging trends and patterns of collaboration. Research mapping techniques are valuable for understanding the research landscape, informing strategic decisions and identifying research gaps and opportunities.

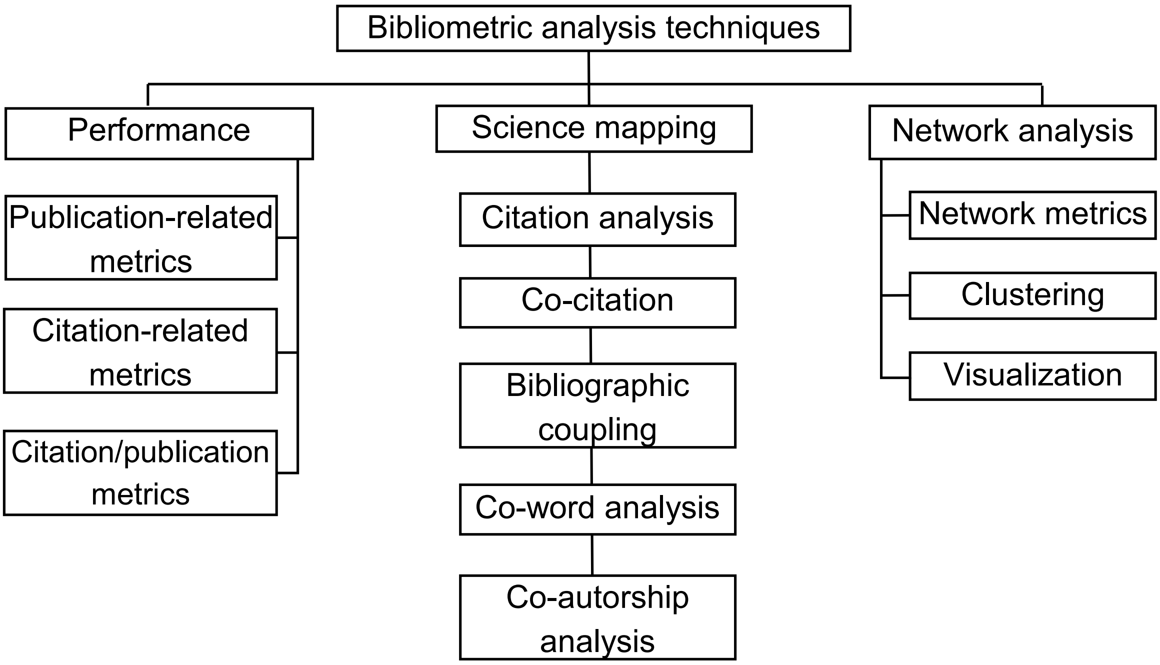

Figure 3. Basic techniques for bibliometric analysis.

Source: modified from Donthu et al., 2021.

The social network analysis is a category of the bibliometric analysis that focuses on the study of relationships and interactions between research entities such as authors, publications or keywords. It involves the analysis of a network structure and properties to gain insights into knowledge flows, collaboration patterns and topic clusters. It enables the mapping of collaborations over time, providing potential researchers with valuable information on how to approach and collaborate with established researchers. It can shed light on specific regions, encouraging collaboration and research development in underrepresented areas. The social network analysis provides a comprehensive picture of social interactions and relationships among researchers, contributing to a deeper understanding of the dynamics of the research field and facilitating strategic decision-making in research planning and resource allocation (Donthu et al., 2021).

The social network analysis as a tool for the bibliometric analysis includes tools and techniques such as network measures, group analysis and visualisation. The basic network measures used in the bibliometric analysis are: Degree of centrality – the number of connections of a research component, indicating its importance and influence in the network; Centrality – measures the ability of a node to connect to other groups of nodes, indicating its role in information flow and knowledge diffusion; Eigenvector centrality – determines the importance of a node based on its connections to other highly connected nodes, highlighting important objects in the network; Clustering coefficient – measures the degree to which nodes in the network tend to cluster together, indicating the presence of research communities or thematic clusters. Visualisation techniques such as network maps and graphs help identify influential researchers, research communities and emerging trends, enabling researchers to make decisions and identify potential researchers or research groups to collaborate with.

One approach to literature mapping is based on the creation of bibliometric networks. Bibliometric networks are networks consisting of nodes and links that represent relationships between different bibliometric entities (van Eck, Waltman, 2014). Nodes in bibliometric networks can represent entities such as publications, journals, researchers or keywords. Links in bibliometric networks indicate relationships between pairs of nodes. The most commonly studied types of relationships in bibliometric networks include citation networks, keyword co-occurrence networks and co-authorship networks. Citation networks refer to links between publications based on their citation patterns. Co-citation networks occur when two publications are cited in a third publication, indicating a relationship between them. Keyword co-occurrence networks represent the occurrence of two keywords in a document's title, abstract or keyword list. Co-authorship networks indicate links between the authors of a document: researchers, research institutions or countries of origin of the authors.

Citation networks are based on direct citations, co-citations and bibliographic links. Citation networks represent links between publications based on citations from other publications. Direct citation networks focus on direct citations between individual publications. On the other hand, co-citation networks analyse the co-citation patterns of publications, where two publications are considered to be co-cited if both are cited by a third publication (van Eck, Waltman, 2014).

Waltman et al. (2010) have proposed a unified approach to bibliometric network mapping and clustering that can be used in the bibliometric network analysis. This approach can be particularly useful when an analysis of a particular research area is required at different levels of detail. It provides a coherent and integrated framework for the bibliometric network analysis, leading to more comprehensive and accurate insights into the structure and dynamics of research networks. This approach can be used to analyse links, shared citations or bibliographic connections between nodes, allowing the identification of relationships and patterns in research networks. Such an approach can be particularly valuable in specific policy contexts, such as policies to support research and technological development.

The visualisation of bibliometric networks using software tools can provide insights into the relationships and forces of influence between publications, researchers and other actors in the field. Van Eck and Waltman (2010) analysed the functionalities of software tools, such as:

- **VOSViewer**: can be used to construct, analyse and visualise bibliometric networks, providing a distance-based and timeline-based visualisation tool.
- **CitnetExplorer**: provides functionality for viewing publication citation networks and offers timeline-based visualisations.
- **HistCite**: focuses on the analysis and visualisation of networks of direct citation relationships between publications – provides timeline-based visualisations of citation networks.

Commonly used sources of scientific literature are indexing platforms, such as Web of Science (WoS), Scopus, Google Scholar and PubMed (Chen, 2017). An analysis by Martín-Martín et al. (2021) showed that Google Scholar found 88% of citations, many of which were not found using other platforms. The second highest performing platform was Microsoft Academic. In most categories, Microsoft Academic found more citations than Scopus and WoS, but had coverage gaps in some areas, such as physics and some humanities categories. Researchers and users of bibliographic databases can make more informed decisions when selecting data sources for their specific information needs. Researchers should consider using multiple data sources to ensure a comprehensive coverage of citations in their field of research. Sources other than the bibliographic ones should also be considered.

Platforms that collect information on patent applications are an important source of knowledge about current directions and trends in research and development. There are several well-known databases and platforms that provide access to patent information: the United States Patent and Trademark Office (USPTO), providing access to a collection of patents and patent applications filed in the United States; the European Patent Office (EPO), providing a comprehensive database of European patents and patent applications; the World Intellectual Property Organisation (WIPO) Patentscope database – providing access to international patent applications filed under the Patent Cooperation Treaty (PCT); Google Patents – a free search engine that allows users to search and discover a wide range of patents from different countries; Espacenet – provided by the European Patent Office, offering a global patent database with millions of patent documents from around the world; Lens.com – indexes scientific articles and patent applications from around the world.

4. Immersive realities: mapping patent applications and discussion

4.1. Patent application profiles

The aim of the systematic review of patent applications was to understand the direction and dynamics of technological solutions for immersive realities. Active patent applications in the lens.com database were searched using a keyword query: (logistics OR (supply AND chain)) AND (reality AND (virtual OR (mixed OR augmented))). This resulted in 16,542 documents from 2004 to 2021, which were further analysed. The content of the collected documents was graphically visualised using the VOSviewer software. The co-occurrence network was structured and visualised on the basis of terms extracted from the metadata.

In the analysis, the threshold for the minimum number of keyword occurrences was set at 170. This allowed 85 keywords that met this threshold to be extracted from a total of 57,875 terms. The total strength of co-occurrence links with other keywords was then calculated. The keywords with the highest total link strength were selected. A two-dimensional map was created using the VOSviewer software (Figure 4).

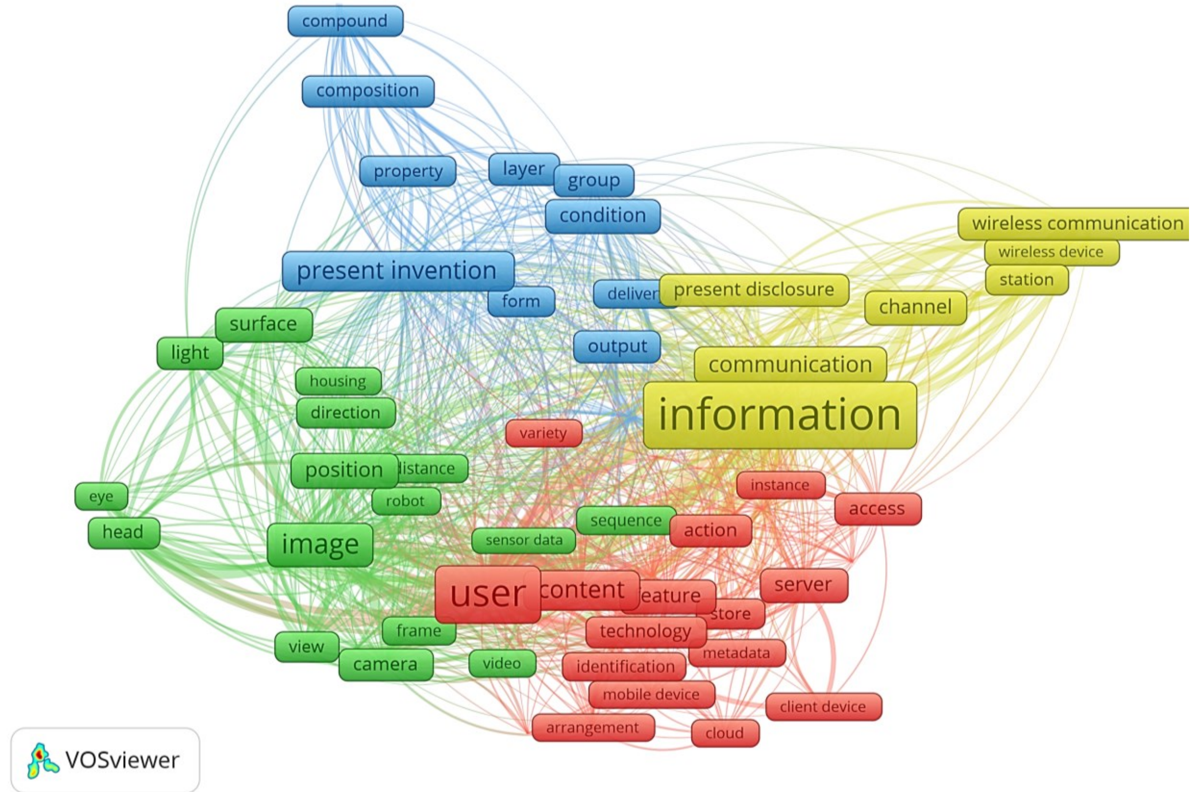

Figure 4. The network of relationships and word groups occurring in abstracts of immersive reality patent applications.

Data Source: metadata from lens.com

Terms with high relevance are grouped into clusters with nodes of different colours and sizes. The relationships between each node are shown as curved lines. The analysis of the terms in each of the four clusters obtained allowed the identification of thematic areas (Table 1). In some clusters, more than one thematic area was mentioned. Central words such as ‘information’, ‘communication’ and ‘image' are clearly visible, indicating that they are key concepts in the context of abstracts of the patent applications examined. Different thematic groups are indicated by four colours: the green group contains words suggesting a link to visual aspects; the red group contains concepts related to user interaction – access and storage of data; the blue group indicates a link to the innovation process; the yellow group relates to communication methods.

Table 1.
Groups of words based on the analysis of words appearing in abstracts of immersive reality patent applications

Group number	Colour	Number of words	Range of subjects
1	red	28	Access and storage
2	green	23	Visualisation
3	blue	19	Innovation process
4	yellow	15	Communication

Data source: metadata from lens.com

The highest number of patent applications during the period was achieved in 2020 (Figure 5a) and this was also the year in which the most patents were granted (1010). The decreasing dynamics of patent applications and granted patents (Figure 5b) may indicate that technologies implementing immersive reality are at a mature stage of the innovation process, so that an intensification of activities related to the diffusion of these solutions in practice can be expected.

The most cited patent (2393 citations) was the patent (Bradski et al., 2016) relating to configurations for presenting virtual and augmented reality experiences to users using image capture devices. The patent was filed in 2015 and allowed in 2019. The patent belongs to the company that filed it – Magic Leap. The analysis of the number of patents applied for and held (Figure 6) shows that LG Electronics (657 applications and 593 patents held) and Qualcomm (539 and 540, respectively) hold the most patents in the studied area. The issue of patent ownership and continued use of patents is related to the possible problems of taking over patents mainly to profit from legal claims rather than using them in business (patent trolling) (Marjak, 2016).

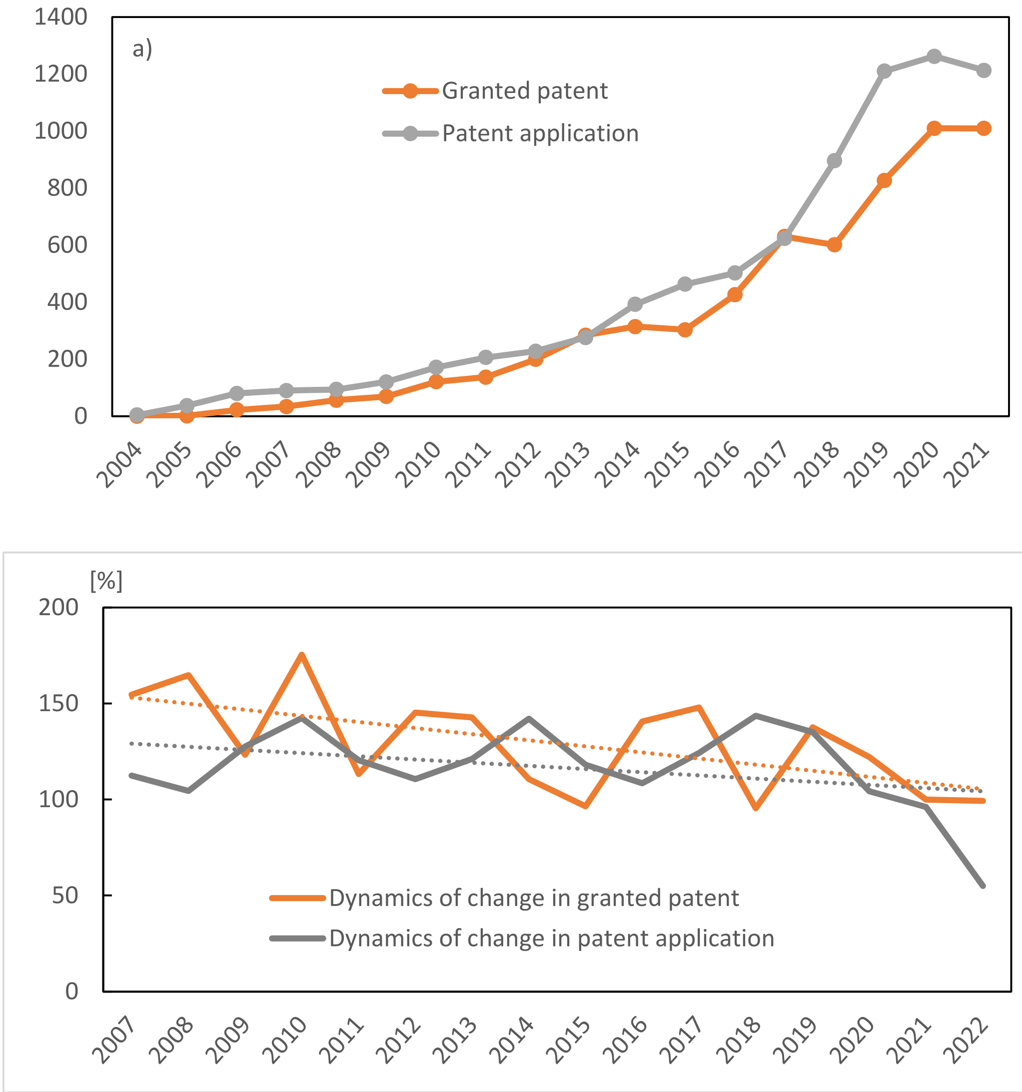

Figure 5. Patent applications and patents granted: a) number (2004-2021) b) dynamics (2007-2021). Data Source: metadata from lens.com

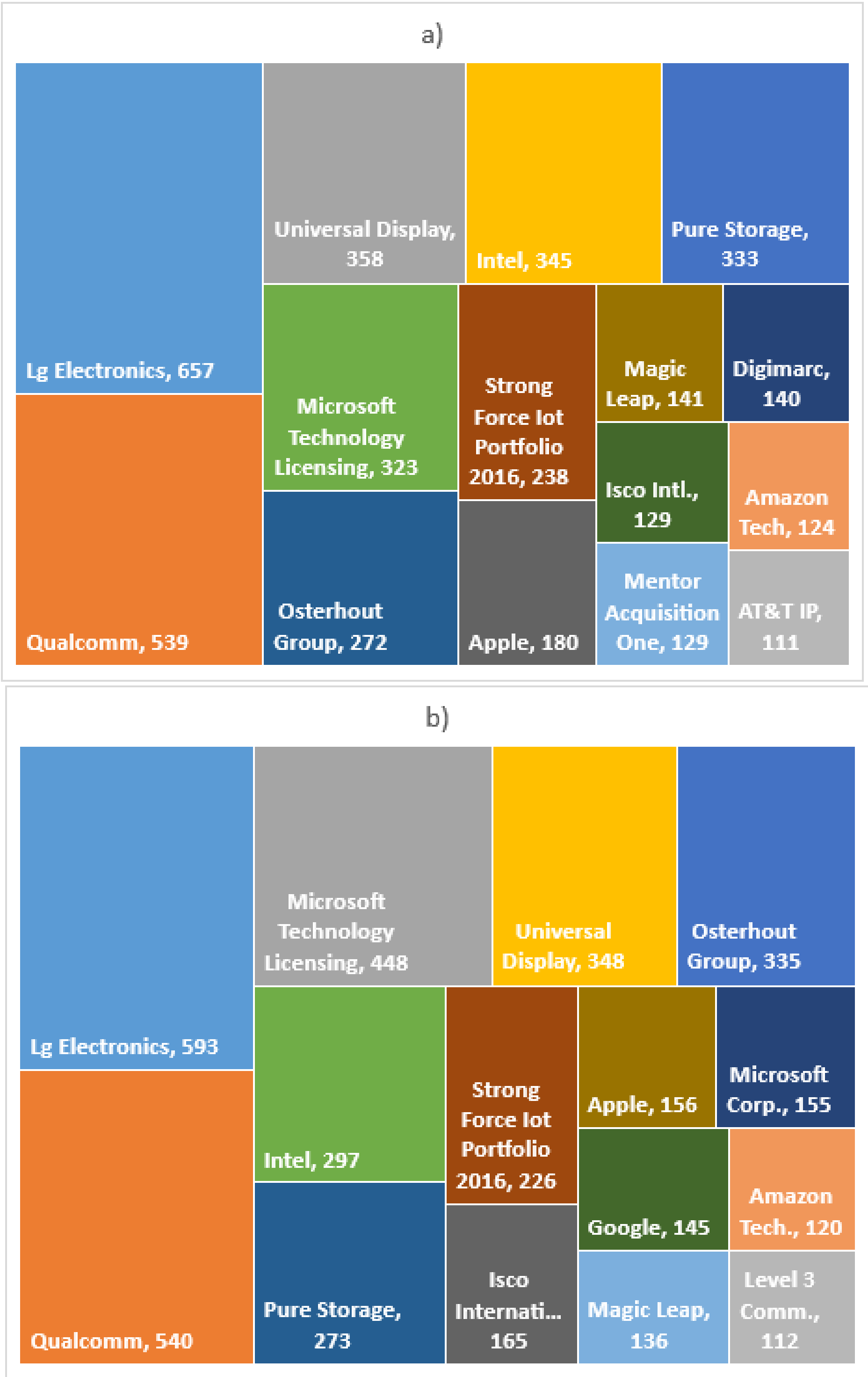

Figure 6. Companies a) the most patent applications; b) owners of the highest number of active patents. Data Source: metadata from lens.com.

4.2. Technological implementation

The use of immersive realities is made possible by appropriate technological solutions. For the most part, immersion into another reality takes place mainly in the realm of visuals – through appropriate head-worn displays (HWDs) and sound through appropriate quality headphones. However, when considering immersive realities, other senses, such as touch for shape recognition cannot be ignored.

Pełka et al. (2019) compared the implementation of VR goggles from different manufacturers. In the comparative analysis, they took into account features such as the weight of the device, the comfort of attaching it to the head, mobility, the overall quality of the displayed image, the sharpness of the edges of the displayed image, the smoothness of the image, the range of accurate vision of the virtual world, the level of eye fatigue, and the overall feeling of use. Based on the tests, users gave an overall rating for the device. The devices tested were at very different levels of technology: Oculus Rift DK2, Vrizzmo, Hykker VR Glasses 3D, Google Cardboard. The Oculus Rift DK2 scored the highest in most categories, but its advantage over the Hykker VR Glasses 3D was not significant. Hykker VR Glasses 3D scored better than Oculus Rift in terms of mobility, edge sharpness, field of view and device weight. Google Cardboard is the simplest and cheapest option, showing that access to virtual reality does not require expensive hardware, such as Oculus Rift (Pełka et al., 2019).

Tests on a larger set of devices were carried out in 2021 (Majdanik et al., 2021). The technical parameters of the devices were tested separately, as well as their operation as Natural User Interfaces (NUI), i.e. those that allow the user to communicate using natural commands such as hand, head or body movements, i.e. implementing technology. The devices tested included: HTC Vive, HTC Vive Cosmos, HTC Vive Pro, Oculus Go, Oculus Quest, Oculus Rift, Oculus Rift S, PlayStation VR, and Samsung Gear VR. The analysis of the technical parameters covered: the weight of the glasses, price on the day of release, and graphics. The natural interface analysis included the following categories: main menu, additional peripherals – gloves, standard peripherals – controllers, and natural motion detection. The best scores in the technical analysis were given to the Oculus devices (most 14 points – Oculus Rift S), while the worst score was given to the HTC Vive Pro with only 7 points. In the natural interface analysis, the HTC Vive device scored the highest with 5 points, but the Oculus Rift goggles came in second with 4 points, so the authors considered the Oculus devices to be the most optimal in terms of technical parameters and implemented NUI.

Research carried out with the VUZIX-M100 device, manufactured by the Vuzix Corporation, a company known for developing visual technology and smart glasses products, has highlighted some problems associated with its implementation, in addition to its benefits (Bal et al., 2023). Data was collected from users through interviews and documents, with durations ranging from 2 to 82 minutes. The non-invasive size and adjustable optics were cited as advantages, while problems with heating and battery life were cited as disadvantages.

Software developers and suppliers worked together to extend the battery life with an external battery, despite the inconvenience of cables.

Research using smart glasses (Microsoft HoloLens) has shown that they work well when humans and robots work together (Kirks et al., 2019). HoloLens is a type of computer that can be worn like a pair of glasses. It helps determine the position and movement of the person wearing it. It looks at how the person is moving and monitors that movement. Tests have been conducted to see how HoloLens can help people and robots share what they see and understand each other's movements. HoloLens can relay information about a person's position to other devices or systems, especially if the person is unable to do so independently.

In the case of immersive devices other than vision ones, interesting research has been carried out with special gloves that allow communication without sound – using hand gestures (Achenbach et al., 2023). The Manus Prime X Haptic gloves being tested are designed for use in virtual reality, enabling natural interactions and a sense of immersion. They are equipped with sensors that can accurately capture hand shapes, which is important for non-verbal communication. They can be calibrated for different hand sizes to ensure accurate data collection. Research has shown that using this type of glove has the potential to detect hand gestures with a high degree of accuracy, which is useful for silent or non-verbal communication in virtual reality. The detailed analysis of gesture recognition led to the conclusion that logistic regression with outlier detection is recommended when a balance between speed and accuracy is required. Accuracy was also affected by hardware limitations, where the use of more accurate gloves could improve results (Achenbach et al., 2023). The smart glove market is volatile, with new companies constantly emerging (Manus VR, SenseGlove, Neurodigital and Sensoryx) and others ceasing their production (Plexus, Teslasuit and VRGluv). The technology is not mature enough yet to deliver satisfactory results across the board (Caeiro Rodriguez et al., 2021).

4.3. Applications in the supply chain

Initially, visualisation techniques in supply chain management were mainly used in manufacturing and logistics simulations (Wenzel et al., 2003). Visualisation techniques can include static methods, such as diagrams, as well as dynamic methods, such as 3D animation and virtual reality. Each of these methods serves different purposes and audiences. Effective visualisation is critical to understanding the simulation results, which can be hindered by inexpressive and ineffective visualisations. A taxonomy of visualisation methods can serve as a decision support tool, guiding users to select the appropriate visualisation technique for specific needs.

Virtual reality (VR) is becoming a useful tool for designing places where products are manufactured or stored (Reif, Walch, 2008). Users can use the software to design products and storage areas, creating 3D spaces. This allows designers to see their designs in 3D as if they were real, helping them understand and plan them more effectively. When testing solutions using AR, it was found that staff using AR took longer to pick orders than when using a paper list. However, AR helped them make fewer mistakes when selecting items. Reasons for the longer turnaround time include the limitations of the technology and the longer time it takes to communicate with the system, as well as the size of the experimental warehouse, which was too small to demonstrate the benefits of AR, which could help find items faster in a larger space.

Virtual reality (VR) is mainly used to train employees in logistics, allowing them to gain experience and learn how to navigate a virtual warehouse, helping them understand the processes, operations and layout of the warehouse without being physically present (Somrak, Guna, 2018). It is also being used to simulate scenes in logistics centres for security training, allowing operational staff to participate in training without regional restrictions, thereby improving training efficiency (Mantovani et al., 2023; Tubis, Rohman, 2023; Ulmeanu et al., 2023). VR is being used to study pedestrian behaviour when interacting with automated vehicles, helping understand how people may react to new technologies on the road (Nuñez Velasco et al., 2019). It allows researchers to create realistic experimental scenarios without the costs and limitations of real-world testing, such as weather and road conditions. It provides the ability to simulate port operations, allowing users to practice tasks, such as crane handling and cargo management in a virtual environment (Jasso et al., 2023; Varriale et al., 2023), as well as freight operations and visualisation of the delivery process, which is particularly useful for last-mile delivery management (Tiwari et al., 2023). VR also supports communication between remote locations, reducing travel and CO2 emissions (Chu, Pan, 2023).

Augmented reality (AR) helps select specific activities by overlaying digital information on the real-world view, showing employees the most efficient routes and item locations (Jasso et al., 2023; Somrak, Guna, 2018; Tubis, Rohman, 2023). AR streamlines item delivery processes, replacing manual tasks, such as reading barcodes, identifying and updating inventory data (Bale et al., 2023). It assists with service advice, allowing information to be annotated and updated without the need for technical manuals or forms (Varriale et al., 2023). It is used to visualise data during machining processes, which can improve interaction in production processes and provide real-time updates (Chu, Pan, 2023; Ulmeanu et al., 2023). AR helps with plant layout planning by visualising machine layout and production line configurations (Tiwari et al., 2023), managing transportation and improving maintenance activities. AR technologies enable real-time monitoring and visualisation of cargo movement, streamlining logistics operations and providing a comprehensive understanding of cargo movement (Mantovani et al., 2023).

Mixed reality (MR), on the other hand, can facilitate remote assistance and collaboration in situations where experts can guide less experienced employees off-site (field service) to solve complex tasks or perform maintenance on refined equipment (Tang et al., 2023). Other applications of MR implemented with Microsoft HoloLens are highlighted in a study conducted by Lang et al. (2019). MR helps guide workers through the component picking process by showing a virtual path and number of components to select, improving efficiency and reducing errors. The technology streamlines the process of preparing component kits for assembly lines by highlighting the correct components and the container for the selected components. It improves decision-making by presenting complex data in a more interactive and understandable way (Wong, Lee, 2024).

4.4. Limitations associated with the use of immersion technologies

The use of immersive reality technology may have limitations in accurately simulating physical sensations, such as weight and texture. The generated reality may not fully capture the complexity of real-world scenarios, which can lead to a gap between virtual practice and real-world performance. These technologies require reliable and fast data connections to work effectively, which can be a challenge in some working environments. The cost of these technologies, including hardware, software and integration with the existing systems, can also be high, which may limit their widespread adoption in smaller organisations (Mantovani et al., 2023; Tiwari et al., 2023). Resistance to change from employees accustomed to traditional methods and a steep learning curve for these solutions can also be an issue (Mantovani et al., 2023; Varriale et al., 2023; Wong, Lee, 2024).

Some AR solutions have failed in the market because they overlay content without building experience, failing to exploit an important feature of this technology – contextual relevance (Rauschnabel et al., 2024). Compatibility issues between the AR software and hardware need to be addressed to ensure the self-sustainability of AR solutions (Chu, Pan, 2023). The effectiveness of AR systems is reduced in smaller spaces, as their potential for wayfinding and reduced search times is better exploited in larger warehouses (Reif, Walch, 2008).

VR can lead to excessive isolation as it immerses users in a completely virtual environment, which can limit collaboration with the real world and other team members (Ulmeanu et al., 2023; Varriale et al., 2023). The use of immersive technology can cause discomfort, eye fatigue, motion sickness and distraction in some users, which may limit its use for longer training sessions and potentially lead to accidents (Jasso et al., 2023; Somrak, Guna, 2018; Tubis, Rohman, 2023).

4.5. Challenges and directions for future work

Future research should focus on developing more industrial immersive reality applications that take full advantage of the unique feature of interacting with virtual objects (Lang et al., 2019). The exploitation of the immersive reality technology potential in industrial applications may be limited due to the lack of coordination of research on this topic (Tang et al., 2023). There is a need for a standardised, modular and open design framework to facilitate the use of AR in supply chain management (Chu, Pan, 2023).

Research into long-term health effects of the use of these technologies is needed to ensure user safety and comfort, improve accessibility for people with disabilities, and support inclusivity (Somrak, Guna, 2018). The economic benefits and potential savings could be highlighted by comparative studies evaluating the cost-effectiveness of virtual reality training compared to traditional methods in logistics and supply chain management (Jasso et al., 2023; Wong, Lee, 2024).

The research should be used to develop tools to assess how the implementation of these technologies would align with the organisation's vision and impact the supply chain coordination and the promotion of sustainable supply chain practices, to identify related barriers and to define the required competencies (Tiwari et al., 2023). They should also include an examination of technical knowledge gaps and skill shortages, which are significant barriers to the successful implementation of these technologies (Tubis, Rohman, 2023).

Future research should also assess how virtual reality (VR), augmented reality (AR) and mixed reality (MR) can be combined with artificial intelligence (AI) to create immersive environments that enhance operational management and training, focusing on areas such as product design, quality control and remote collaboration to reduce working time and improve overall business performance (Varriale et al., 2023). They should also address integration with other advanced technologies, such as machine learning, sensor technologies, the Internet of Things, and blockchain (Wong, Lee, 2024).

5. Conclusions

The integration of virtual realities, such as Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR) into supply chain management has transformative potential for operational practices, improving operational efficiency and decision-making capabilities. The research highlights the multifaceted impact of immersive realities on sustainability, from improving supply chain management and consumer product interaction to contributing to more sustainable urban planning and healthcare practices. These technologies facilitate quality control processes, enable effective training and skill development for operators, and support remote collaboration and decision-making among supply chain stakeholders.

The systematic review of patent applications is aimed at understanding trends and dynamics in immersive reality technologies. The analysis was conducted using 16,542 documents from 2004-2021 and the VOSviewer software to visualise and structure the network based on terms derived from metadata. A two-dimensional map was generated, highlighting four thematic clusters, identifying key terms such as 'information', 'communication' and 'image' as key in the context of immersive reality patents. These clusters represent visual aspects, user interaction, innovation processes and communication methods, indicating the multidisciplinary nature of immersive reality technologies. The most cited patent relates to virtual and augmented reality experiences using image capture devices.

Immersive reality technologies facilitate user engagement through visual and audio devices, especially wearable displays and high quality headphones, but the integration of other senses, such as touch for shape recognition, remains crucial. Initially, visualisation techniques in supply chain management were mainly used in production and logistics simulations, incorporating both static methods, such as charts and dynamic methods, such as 3D animation and virtual reality (VR), each serving different purposes and audiences. Effective visualisation is crucial to understanding simulation results, and a taxonomy of visualisation methods helps select appropriate techniques for specific needs. VR has proven to be a valuable tool in the design of manufacturing and warehousing spaces, improving planning through realistic 3D visualisations, and has been essential in the training of logistics personnel by simulating warehouse operations and safety training scenarios without geographical constraints. Augmented reality (AR) improves the efficiency of item selection by overlaying digital information on the real view, optimising delivery processes and maintenance operations. Mixed reality (MR) facilitates remote assistance and collaboration, guiding less experienced workers through complex tasks using devices such as Microsoft HoloLens, improving efficiency and reducing errors in component assembly and maintenance tasks.

The technologies studied face challenges related to the accuracy of simulating physical impressions and the complexity of real-world scenarios, potentially leading to a performance gap between virtual practice and real-world performance. High costs, resistance to change and steep learning curves may limit widespread adoption, particularly in smaller organisations. In addition, issues such as AR compatibility, VR-induced isolation and user discomfort may further limit the effective use of these technologies in different environments.

Future research should focus on developing industrial applications of immersive reality to exploit the unique feature of interacting with virtual objects, addressing the lack of coordinated research and the need for a standardised, modular and open design framework to facilitate the application of AR in supply chain management. The long-term health effects of these technologies, their economic benefits and their feasibility compared to traditional logistics and supply chain management training methods should also be investigated. In addition, research should aim to integrate VR, AR and MR with artificial intelligence and other advanced technologies, such as machine learning, sensor technologies, IoT and blockchain to improve operations management, with a focus on product design, quality control and remote collaboration to enhance business efficiency.

References

1. Achenbach, P., Laux, S., Purdack, D., Müller, P.N., Göbel, S. (2023). Give Me a Sign: Using Data Gloves for Static Hand-Shape Recognition. *Sensors, 23(24),* 9847. https://doi.org/10.3390/s23249847.
2. Alberto Martín-Martín, Thelwall, M., Orduna-Malea, E., Delgado López-Cózar, E. (2021). Google Scholar, Microsoft Academic, Scopus, Dimensions, Web of Science, and OpenCitations' COCI: A multidisciplinary comparison of coverage via citations. *Scientometrics, 126(1)*, pp. 871-906. https://doi.org/10.1007/s11192-020-03690-4.
3. Bal, M., Vermeerbergen, L., Benders, J. (2023). Putting head-worn displays to use for order picking: A most-similar comparative case study. *International Journal of Logistics Management, 34(5)*, pp. 1475-1499. Scopus. https://doi.org/10.1108/IJLM-12-2021-0570.
4. Bale, A.S., Joy, S., Baby Chithra, R., Rithish Revan, S., Vinay, N. (2023). 4 Augmented reality in cross-domain applications. *Augmented and Virtual Reality in Social Learning: Technological Impacts and Challenges, Vol. 3.* De Gruyter, pp. 43-62. https://doi.org/10.1515/9783110981445-004.
5. Bhavadharini, B., Monica, V., Anbarasan, R., Mahendran, R. (2023). Virtual, augmented, and mixed reality as a versatile tool in food consumer behavior evaluation: Recent advances in aroma, taste, and texture incorporation. *Comprehensive Reviews in Food Science and Food Safety, 22(6),* pp. 4925-4956. https://doi.org/10.1111/1541-4337.13248.
6. Bradski, G.R., Miller, S.A., Abovitz, A. (2015). *Methods And Systems For Creating Virtual And Augmented Reality* (Patent No. US 2016/0026253 A1). https://lens.org/131-928-864-170-858.
7. Büscher, S., Lorenz, S. (2023). 7 Mixed Reality Systems in the Participation in Urban Land Use Planning. In: *Innovations and Challenges of the Energy Transition in Smart City Districts* (pp. 109-118). De Gruyter.
8. Caeiro-Rodriguez, M., González, I., Mikic-Fonte, F., Llamas-Nistal, M. (2021). A Systematic Review of Commercial Smart Gloves: Current Status and Applications. *Sensors, 21*, p. 2667. https://doi.org/10.3390/s21082667.
9. Cai, Y.-J., Lo, C.K.Y. (2020). Omni-channel management in the new retailing era: A systematic review and future research agenda. *International Journal Of Production Economics, 229*, p. 107729. https://doi.org/10.1016/j.ijpe.2020.107729
10. Chadha, G.K., Punhani, R., Saini, S. (2023). 3 Merging of artificial intelligence (AI), artificial life (AL) and virtual reality (VR). *Artificial Intelligence for Virtual Reality, Vol. 14.* De Gruyter, pp. 27-44. https://doi.org/10.1515/9783110713817-003.
11. Chen, C. (2017). Science Mapping: A Systematic Review of the Literature. *Journal of Data and Information Science, 2(2)*, pp. 1-40.

12. Chu, C.-H., Pan, J.-K. (2023). A Systematic Review on Extended Reality Applications for Sustainable Manufacturing Across the Product Lifecycle. *International Journal of Precision Engineering and Manufacturing-Green Technology, 11,* pp. 1017-1028. https://doi.org/10.1007/s40684-023-00567-8.
13. Cipresso, P., Giglioli, I.A.C., Raya, M.A., Riva, G. (2018). The Past, Present, and Future of Virtual and Augmented Reality Research: A Network and Cluster Analysis of the Literature. *Frontiers in Psychology, 9*, 309500.
14. Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., Lim, W.M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research, 133*, pp. 285-296. Scopus. https://doi.org/10.1016/j.jbusres.2021.04.070.
15. Fross, K., Szuliński, T., Fross, R. (2022). Mieszana rzeczywistość w projektowaniu BIM i inspekcjach budowli. *Builder, 26(12)*, 8-11. https://doi.org/10.5604/01.3001.0016.0920.
16. Hořejší, P. (2015). Augmented Reality System for Virtual Training of Parts Assembly. *Procedia Engineering, 100*, pp. 699-706. https://doi.org/10.1016/j.proeng.2015.01.422.
17. Jasso, J., Cruz, Z., Álvarez, J. (2023). Applying Virtual Reality for Port Logistics Learning. *2023 IEEE International Conference on Engineering Veracruz (ICEV)*, pp. 1-5. https://doi.org/10.1109/ICEV59168.2023.10329707.
18. Kirks, T., Jost, J., Uhlott, T., Pueth, J., Jakobs, M. (2019). Evaluation of the Application of Smart Glasses for Decentralized Control Systems in Logistics. *2019 IEEE Intelligent Transportation Systems Conference (ITSC)*, pp. 4470-4476.
19. Lang, S., Kota, M.S.S.D., Weigert, D., Behrendt, F. (2019). Mixed reality in production and logistics: Discussing the application potentials of Microsoft HoloLensTM. *Procedia Computer Science, 149*, pp. 118-129. https://doi.org/10.1016/j.procs.2019.01.115.
20. Li, X., Yi, W., Chi, H.-L., Wang, X., Chan, A.P.C. (2018). A critical review of virtual and augmented reality (VR/AR) applications in construction safety. *Automation in Construction, 86,* pp. 150-162. https://doi.org/10.1016/j.autcon.2017.11.003.
21. Liaropoulos, A.N. (2023). Digitizing the battlefield: Augmented and virtual reality applications in warfare. In: *Routledge Handbook of the Future of Warfare* (pp. 308-318). Routledge; Scopus. https://doi.org/10.4324/9781003299011-33.
22. Liberatore, M.J., Wagner, W.P. (2021). Virtual, mixed, and augmented reality: A systematic review for immersive systems research. *Virtual Reality, 25(3)*, pp. 773-799. https://doi.org/10.1007/s10055-020-00492-0.
23. Majdanik, D., Madoń, A., Szymczyk, T. (2021). Natural interfaces in VR - comparative analysis. *Journal of Computer Sciences Institute, Vo1. 8,* pp. 1-6. https://doi.org/10.35784/jcsi.2385.
24. Mantovani, C., Pavanatto, L., Pinho, M.S. (2023). A Framework for Monitoring Cargo Movement using Virtual Reality. *Proceedings of the 25th Symposium on Virtual and Augmented Reality*, pp. 259-263. Scopus. https://doi.org/10.1145/3625008.3625040.

25. Marjak, H. (2016). Negatywne zjawiska związane z rozwojem innowacyjności: Patent trolling. In: *Działalność innowacyjna przedsiębiorstw w Polsce—Dylematy i sposoby wspierania środkami Unii Europejskiej* (pp. 199-213). CeDeWu.
26. Milgram, P., Colquhoun, H.W. (1999). Chapter 1a Taxonomy of Real and Virtual World Display Integration. In: *Augmented Reality*.
27. Paradiso, J.A., Landay, J.A. (2009). Guest Editors' Introduction: Cross-Reality Environments. *IEEE Pervasive Computing*, *8(3),* pp. 14-15. https://doi.org/10.1109/MPRV.2009.47.
28. Pełka, Ł., Podstawka, Ł., Szymczyk, T. (2019). Analiza porównawcza gogli do VR. *Journal of Computer Sciences Institute, 10*, pp. 36-43.
29. Radhika, K.B.K., Bharany, S. (2023). 10 Augmented Reality and Virtual Reality in disaster management systems: A review. *Handbook of Augmented and Virtual Reality, Vol. 1.* De Gruyter, pp. 155-174. https://doi.org/10.1515/9783110785234-010.
30. Radianti, J., Majchrzak, T.A., Fromm, J., Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers & Education, 147,* p. 103778. https://doi.org/10.1016/j.compedu.2019.103778.
31. Rauschnabel, P.A., Felix, R., Heller, J., Hinsch, C. (2024). The 4C framework: Towards a holistic understanding of consumer engagement with augmented reality. *Computers in Human Behavior, 154*, p. 108105. https://doi.org/10.1016/j.chb.2023.108105.
32. Reif, R., Walch, D. (2008). Augmented & Virtual Reality applications in the field of logistics. *The Visual Computer, 24(11),* pp. 987-994. https://doi.org/10.1007/s00371-008-0271-7.
33. Sarkar, A., Bansal, M., Lea, D., Bura, D. (2023). 1 Virtual reality: A simulated experience: a comprehensive view. In: J. Hemanth, M. Bhatia, I. De La Torre Diez (Ed.), *Artificial Intelligence for Virtual Reality* (pp. 1-14). De Gruyter. https://doi.org/10.1515/9783110713817-001.
34. Schnabel, M.A., Wang, X., Seichter, H., Kvan, T. (2007). From Virtuality to Reality and Back. *Proceedings of the International Association of Societies of Design Research, 1*, *1,* pp. 15-129.
35. Sharma, S., Chamoli, N. (2023). 8 Merging of artificial intelligence (AI) with virtual reality (VR) in healthcare. In: In J. Hemanth, M. Bhatia, I. De La Torre Diez (Ed.), *Artificial Intelligence for Virtual Reality* (pp. 103-128). De Gruyter. https://doi.org/10.1515/9783110713817-008.
36. Skalski, A., Stanuch, M., Złahoda-Huzior, A., Kuszewski, T. (2020). Wykorzystanie mieszanej rzeczywistości w zakresie wizualizacji obrazowych danych trójwymiarowych. *Inżynier i Fizyk Medyczny, 9(3)*, pp. 193-198.

37. Somrak, A., Guna, J. (2018). Overview of devices and technologies in the area of virtual- ,augmented-, and mixed-reality applications. *Elektrotehniski Vestnik [Electrochemical Review], 85(1-2)*, pp. 54-61.
38. Tang, Y.M., Au, K.M., Lau, H.C. W., Ho, G.T.S., Wu, C.H. (2020). Evaluating the effectiveness of learning design with mixed reality (MR) in higher education. *Virtual Reality, 24(4)*, pp. 797-807. https://doi.org/10.1007/s10055-020-00427-9.
39. Tang, Y.M., Kuo, W.T., Lee, C.K. (2023). Real-time Mixed Reality (MR) and Artificial Intelligence (AI) object recognition integration for digital twin in Industry 4.0. *Internet of Things, 23*, p. 100753. Scopus. https://doi.org/10.1016/j.iot.2023.100753.
40. Tiwari, S., Baral, S.K., Goel, R. (2023). Application of AR and VR for supply chain: A macro perspective approach. In: *Augmented and Virtual Reality in Industry 5.0* (pp. 1-18). Scopus. https://doi.org/10.1515/9783110790146-001.
41. Tubis, A.A., Rohman, J. (2023). Intelligent Warehouse in Industry 4.0—Systematic Literature Review. *Sensors, 23(8),* p. 4105. https://doi.org/10.3390/s23084105.
42. Ulmeanu, M.-E., Dijmărescu, M.-R., Abaza, B.-F., Szuder, A., Doicin, C.-V. (2023). Digital Manufacturing Pilot Study for Stepping Towards Mixed Reality Applications in Tertiary Education. *Leveraging Transdisciplinary Engineering in a Changing and Connected World, Vol. 41*. IOS Press; Scopus, pp. 643-652.
43. Van Eck, N.J., Waltman, L. (2014). Visualizing Bibliometric Networks. In: Y. Ding, R. Rousseau, D. Wolfram (Eds.), *Measuring Scholarly Impact: Methods and Practice* (pp. 285-320). Springer International Publishing. https://doi.org/10.1007/978-3-319-10377-8_13.
44. Varriale, V., Cammarano, A., Michelino, F., Caputo, M. (2023). Critical analysis of the impact of artificial intelligence integration with cutting-edge technologies for production systems. *Journal of Intelligent Manufacturing*, pp. 1-33. https://doi.org/10.1007/s10845-023-02244-8.
45. Velasco, J.P.N., Farah, H., Van Arem, B., Hagenzieker, M.P. (2019). Studying pedestrians' crossing behavior when interacting with automated vehicles using virtual reality. *Transportation Research Part F: Traffic Psychology and Behaviour, 66*, pp. 1-14. https://doi.org/10.1016/j.trf.2019.08.015.
46. Waltman, L., Van Eck, N.J., Noyons, E.C.M. (2010). A unified approach to mapping and clustering of bibliometric networks. *Journal of Informetrics, 4(4)*, pp. 629-635. https://doi.org/10.1016/j.joi.2010.07.002.
47. Wenzel, S., Bernhard, J., Jessen, U. (2003). A taxonomy of visualization techniques for simulation in production and logistics. *Proceedings of the 2003 Winter Simulation Conference*, *1*, pp. 729-736. https://doi.org/10.1109/WSC.2003.1261489.

48. Wong, E.Y.C., Lee, P.T.Y. (2024). Virtual reality in transportation and logistics: A clustering analysis of studies from 2010 to 2023 and future directions. *Computers in Human Behavior*, *153*, p. 108082. https://doi.org/10.1016/j.chb.2023.108082.
49. Yadav, S.S., Chauhan, V., Arora, N., Singh, V., Verma, J. (2023). 6 Challenges and the future of artificial intelligence in virtual reality in healthcare. *Artificial Intelligence for Virtual Reality, Vol. 14*. De Gruyter, pp. 71-86. https://doi.org/10.1515/9783110713817-006.