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Taxonomical analysis of the virtuality continuum components

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Abstract. The aim of the research was to develop a universal virtuality continuum model for future grouping and structuring of applicable technologies and their future potential analysis. The object of research was the continuum of virtuality as a theoretical model of interaction of the real and virtual world. The problem addressed was the lack of specific terminological base and conditions for dividing the elements of virtuality, which hinders their inclusion in science, business, and everyday life. To reach a solution, the paper did a taxonomic investigation of components of the continuum, namely: Extended Reality (XR), Mixed Reality (MR), Virtual Reality (VR), Augmented Reality (AR) and Augmented Virtuality (AV). It offered a generalised conceptual framework which reveals their interdependencies, shared and distinguishing features. According to the findings of the research, XR technology received the highest score (4.00/5) because it combined the benefits of VR, AR, and AV. AR experienced high autonomy and mobility (3.57/5), hence it was convenient for mobile application. VR (3.43/5) was defined by its popularity and availability of the equipment. MR (2.57/5) was rated lower due to its high technical complexity to implement and AV (2.43/5) due to its limited applications and high cost to implement. The conclusions of the study were made on the grounds of formal object classification algorithms and comparison thereof on seven dimensions: mobility, autonomy, affordability, popularity, market growth, applicability, technological maturity. The method was distinguished by the integration of concept base analysis with consideration of practical examples of technology use in various industries, and quantitative analysis based on open-source statistics. The practical value of the results lies in their potential application in the development of user interfaces, the design of advanced information technology tools, and the modelling of virtual environments. The obtained indicators are determined by the high accuracy of the analysis, which is directly proportional to the number of characteristics considered

Keywords: virtual technologies; prospect index; taxonomic analysis; technological maturity; market indicators; mobility

Introduction

The current period of large-scale development of information technologies introduces new problems into the integration of virtual and actual worlds into a single concept – the continuum of virtuality. Despite great interest and broad application of Extended Reality (XR), Augmented Reality (AR), Mixed Reality (MR), Virtual Reality (VR), and Augmented Virtuality (AV) technologies in education, medicine, e-commerce, entertainment, and industry, to date there has not been a solution to the issue of a structured classification system for the technologies. Unspecified technical standardisation has the implication of an enormous slowdown of the rate of progress of the industry

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as anticipated, and thus the loss of opportunity for potential investment. The systematic review of AR system evaluation metrics by O. Kanarskyi *et al.* (2022) contributed to advancing one axis of the taxonomy through quality dimensions. Besides this, E. O'Hara *et al.* (2024) have explored the ergonomic and usability issues of using AR in clinical environments, underlining that human-machine interaction parameters should be included in taxonomic models. L. Duan *et al.* (2022) introduced the concept of visual confusion in AR: it thus proposes a perceptual criterion for distinguishing layers in the continuum of virtuality. Meanwhile, J. Hu (2024) and T. Blackman & D. Harley (2024) illustrated how head-mounted spatial computing devices blur boundaries among VR, AR, and MR, and their implications for revising the taxonomy. Furthermore, X. Guo *et al.* (2025) have underlined that while VR/XR applications mature and face challenges around security and privacy, their system lifecycle and risk classification should also be part of the taxonomy.

These contributions all have pointed towards a multi-dimensional taxonomy of virtuality – covering interaction mode, degree of immersion, device type, perceptual quality, risk domain, and application context – which has yet to be fully formalised and adopted by the community. The need for systematisation of concepts, methods, means, and criteria for classification is because of the need to increase accuracy in practical solutions and rational usage of technical assets. Particularly, terminological vagueness leads to model and method application error, duplication of functions, overcomplexification of user experience, and loss of efficiency of system-user interaction. Therefore, the research related to the conceptualisation of a foundation and comparative analysis of the components of the virtuality continuum is relevant. The classification system developed reduces current uncertainty about the components of this field, promoting recognition of the typical and usual characteristics of each technology, and comparative analysis based on statistical data from open sources will serve as a basis for investor and developer recommendations. The aim of the study was to create a sorted conceptual model of the virtuality continuum elements and compare them by the criteria of mobility, autonomy, affordability, popularity, market growth, applicability, and the stage of technological maturity by current statistics and forecasts. For this aim, two main tasks were set. First, it was necessary to classify and describe XR, MR, AR, AV, and VR as components of the virtuality continuum. Second, the study sought to compare and evaluate the prospects of these technologies based on a set of general criteria, using statistical data obtained from open sources.

Literature Review

In spite of the enormous quantity of works dedicated to this subject, the internal nature of the continuum remains insufficiently theoretically proven. According to the analysis of sources, it can be emphasised that the majority of authors are concerned with technical nature of situational solutions or taking into consideration actual situations for their application, not systematising the concepts composing a single reality – virtuality scale. The initial publication of P. Milgram *et al.* (1995) formed the theoretical fundament for the explanation of the phenomenon of the continuum of virtuality, even in the case of the impossibility of predicting the further development of the discipline due to scientific progress and technological achievements. The issue of distinct formulation of the characteristics of each element of the continuum and the development of conditions for their distinction is also relevant. The main reason for this is the comparative recency of the field of study, which hindered its capacity to predict the current technical and methodological requirements. The work of X. Tu *et al.* (2023) set the background for the industrial use of virtual assistants but failed to highlight methods of matching XR modelling for subsequent use in learning. This was due to the industrial nature of the main research line. M. Casini (2022) and C. Coupry *et al.* (2021), writing in the context of applying XR to the simulation of smart buildings, focused primarily on technological aspects, while overlooking the issue of systematising and generalising users' experiences, particularly with regard to its interdisciplinary character. This can be explained by the focused nature of the projects, which did not necessitate the design of a distribution system by categories. S.H.-W. Chuah (2019) identified the issue of harmonising XR technology but did not address it in conjunction with the problem of terminological ambiguity. Such instances of a lack of ontological foundation are typical in applied marketing research. The studie conducted by A. Gruca *et al.* (2020) illustrated applications of AR technologies but did not provide a clear distinction between different components.

R.T. Azuma's (1997) influential work was a key force in current development of AR ideas, though the author does not touch on AR under its associated topics. Taxonomic study is avoided due to necessity to categorize equipment and thus theoretical concerns can be neglected. B. Sobota *et al.* (2020) alluded to the topic of MR, thus only schematically outlining its boundaries without revealing the element of common identification in relation to adjacent components. Although the authors were aware of the problem, they did not propose either an ontological model or an applied method of differentiation. This was due to the limited level of abstraction in the research. In the historically valuable source of L.B. Rosenberg (1992), the theory was set at the time of MR's introduction but the problem of harmonising criteria for comparing AR, VR, MR, XR, and AV wasn't solved. This is due to the fact that the systems at that time were not highly capable. Similarly, T.P. Caudell & D.W. Mizell (1992) set down basic principles of AR but does not categorize them as part of a vast collection of technologies. The age of the study leads to vagueness in definitions. In M. Möhring *et al.* (2004), the focus was on visualisation via AR through cell phones, and scaling the technology in non-standard situations remained an unresolved problem, due to an emphasis on demonstrating potential rather than on functional expansion. The material from IT-Enterprise (n.d.) was limited to describing the state of affairs in the industry, but it lacked theoretical reflection, systematisation, or critical analysis. Such a source could, at best, assist in popularising the subject, but otherwise made little contribution to its development. Statistical data from M. Dey & R. Jambhale (2025) and T. Pangarkar (2025) illustrated AR and VR implementation patterns but did not provide explanations for the skewed distribution or strategies for predicting future trends. This was because the sources themselves were presented in an extremely aggregate graphical form, without any research underpinning. The works of G. Bruder *et al.* (2010), S. Schmidt *et al.* (2015), and A. Gruca *et al.* (2020), as examples of the use of AR technologies, did not make a clear distinction between other components. A common problem was the lack of a conceptual framework, as applied modelling focused on practical application without a methodological foundation. Although there was an attempt to accommodate the nomenclature, V. Volynets (2021) did not provide a typology of the virtuality continuum per se, presenting it instead in a compiled review format. The full extent of the research was not reflected. Overall, based on the critical analysis, it could be concluded that no conceptual framework of the elements of the virtuality continuum existed in the scientific literature that would allow AR, VR, XR, MR, and AV to be clearly and unequivocally defined, categorised, and compared according to a single set of criteria. All the reviewed sources left certain aspects unresolved: general clear delimitation of the continuum components (especially MR and XR); failure to unified classification based on formal features due to technical possibility and the level of development of the industry; inadequate substantiation of prospects for each component. These issues had not yet been resolved, primarily due to objective factors, as the rapid pace of technological advancement outstripped the development of a theoretical foundation, while industrial research priorities took precedence over systematic and theoretical approaches, and no consensus or sufficiently developed discussion had emerged among researchers in the field. A common unresolved problem that has stemmed from a critical assessment of sources is the lack of one theoretically justified concept base for the components of the virtuality continuum that would render them theoretically classifiable exactly and comparable to judge through a single system of common criteria.

Materials and Methods

The study assumes that the components of the virtuality continuum are interrelated, but can be considered as separate technologies or conceptual models. It is also assumed that the current level of technological development is sufficient for an objective assessment of the parameters and capabilities of each component. The main hypothesis was that the taxonomy of the virtuality continuum components and the comparative analysis in terms of mobility, autonomy, accessibility, popularity, market growth, applicability, and technological maturity would become a tool for systematising the industry and driving the development of applied solutions for technical, educational, and business use. The study was conducted based on open sources, without creating and testing new hardware solutions. The concept of "immersiveness" is considered as a generalised indicator of user engagement in the virtual environment without in-depth psychophysiological analysis. The methods used in the research are shown in Figure 1.

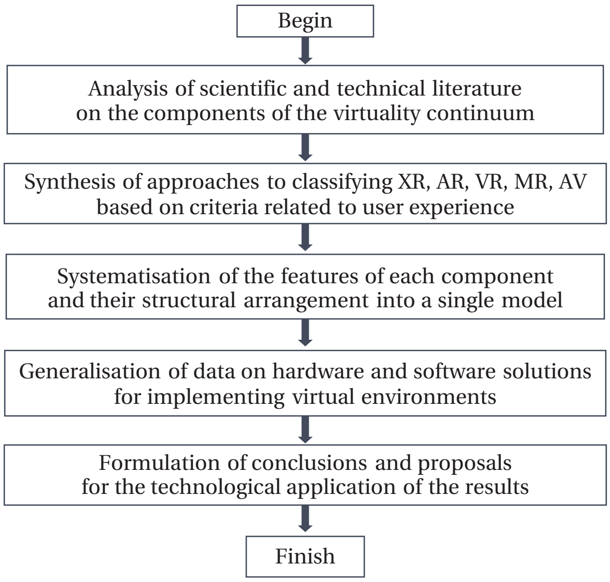

Figure 1. Research methodology
Source: developed by the authors

A detailed analysis of contemporary scientific articles, technical reports, papers, and reviews devoted to the concept of the virtuality continuum was conducted, with the main focus placed on the conceptual definitions and characteristics of technologies such as augmented, mixed, virtual, and XR, as well as augmented virtuality. Based on the sources studied, a synthesis of XR, AR, VR, MR, and AV classification methods according to user experience criteria was carried out, with various approaches generalised by considering their shared characteristics of effectiveness. This enabled the creation of a system of comparative criteria for precise analysis. Furthermore, the features and characteristics of each component were systematised and structurally organised into a single comprehensive model. This systematisation made it possible to clearly demonstrate the interconnection and distinction between XR, AR, VR, MR, and AV technologies. Data on hardware and software solutions for the implementation of virtual environments were compiled by analysing current technologies used to create and sustain virtual content, including VR headsets, AR glasses, mobile devices, and modelling and visualisation software. Particular attention was placed on the technical specifications, functional capabilities, and applicability range of each solution. Based on the obtained results, practical conclusions were drawn regarding the potential use of specific technologies in relevant fields such as education, industry, medicine, and architecture. Trends and priority directions for future research were also identified, with the aim of developing a theoretical foundation to enhance the efficiency of scientific and engineering activities. The research process involved the use of information processing software, including Microsoft Excel for creating comparative tables and graphs, as well as graphic editors for constructing illustrative diagrams. The essence of the study was to compare the five prevailing types of virtuality continuum technologies (VR, AR, XR, MR, AV) along seven criteria: mobility, autonomy, affordability, popularity, market growth, applicability, and technological maturity (Table 1).

Table 1. Criteria for comparing the elements of the virtuality continuum

Type of criterion	Description
Mobility	The ability to use the devices while moving and outside
Autonomy	The ability of devices to work independently without outside hardware (PC, trackers, etc.)
Affordability	Typical cost of devices available in the market
Popularity	The scope of implementation, mass application, and users
Market growth	The rate of growth of the global market for every technology
Applicability	The number of spheres of application
Technological maturity	The degree of technology development and the readiness of solutions for mass application

Source: developed by the authors

The Table 1 synthesised key criteria for evaluating the components of the virtuality continuum, providing a structured framework to assess their practical, technological, and market-related attributes. It allows for a comparative analysis of different technologies based on factors influencing usability, adoption, and readiness for implementation. The methodological basis of the study covers a taxonomic approach to classification, which involves the construction of a hierarchical system of concepts, and the use of a five-point rating scale to compare components according to common criteria (Table 2).

Table 2. Criteria for assessing components of the virtuality continuum

Level / Criterion	1	2	3	4	5
Mobility	Fully stationary solutions	Bulky, limited in mobility (e.g. PC headsets)	Requires partial fixation, often bound to the indoor environment	Portables, possibly with some limitations (size, outdoors brightness, autonomy)	Glasses or easy-to-wear headsets, no wires required, work properly outdoors or on the move
Autonomy	Completely reliant on other systems	Constant connectivity to a PC or a server required	Partial autonomy (e.g., autonomy only for viewing media)	Autonomous, but with limited operation time or requiring a smartphone	Fully autonomous devices with build-in processor, battery and sensors
Affordability	> $2,500 (high cost, corporate solutions)	$1,000-2,500 (professional segment)	$500-1,000 (mid-range segment)	$300-500 (affordable to the mass user)	< $300 (very low cost, consumer segment)
Popularity	Almost no general acceptance	Limited use, mainly for tests or demos	Used in a limited number of industries, slow expansion	Regular mass presence, rapid growth	Tens of millions of active users
Market growth	The market is decreasing or static	The market is unstable or growing slowly	Medium growth	Growth with investors on site	The market is growing over 20% per year, large-scale development is predicted
Applicability	Limited usage	1 main field	2-3 main fields	4 or more fields of application	Used in the majority of industries
Technological maturity	Only experimental works or ideas	Limited solutions, risky operation	In the stage of active development, working prototypes	Mature, but still with fragmentation	Technologically mature, supported by corporations, mass production

Source: developed by the authors

Each of the criteria is evaluated on a five-degree scale: 1 – low degree, 5 – very high degree. The evaluation of each degree is conditional degrees to compare with essential differences, each of which is presented in the corresponding paragraphs of Table 2. The selection of an appropriate degree is made according to statistical data obtained from open sources (Pangarkar, 2025; Dey & Jambhale, 2025). Then, the mean rating value was computed as an overall measure of the prospects for the technology. The value of the prospect index P is calculated using the following formula:

$$P = \frac{1}{n}\sum_{i=1}^{n} p_i, \qquad (1)$$

where p_i – a list of evaluation criteria for each component from Table 1; n – the number of criteria entered into the table.

Research conditions: the analysis was performed in a virtual environment, using available open sources, including scientific publications, technical reviews, patent documentation, and AR/VR technology market analytics. No physical experiments or hardware testing were conducted as part of the research. Thus, the study was carried out through critical reflection on existing theoretical developments, interpretation of the current state of technology, and construction of a conceptual model of the components of the continuum and their comparative analysis based on a generalisation of literary sources.

Results and Discussion

Classification and characteristics of XR, MR, AR, AV, and VR components of the virtuality continuum. The subject of investigation is the notion of the "reality – virtuality" continuum, or virtuality as an uninterrupted continuum from entirely virtual (Virtuality) to entirely real (Reality), introduced for the first time by P. Milgram *et al.* (1995). Attention was given to the structural formalisation of the "reality – virtuality" continuum, encompassing all variations and combinations of real and virtual objects (Fig. 2). The span of all the mixes in the use of virtual parts together is differentiated from the span of pure reality and forms a set that is generically referred to as XR. The space between the two extremes, where the real and the virtual mix, is referred to as MR and encompasses AR, whereby the virtual is overlaid onto the real, and augmented virtuality, whereby the real is overlaid onto the virtual.

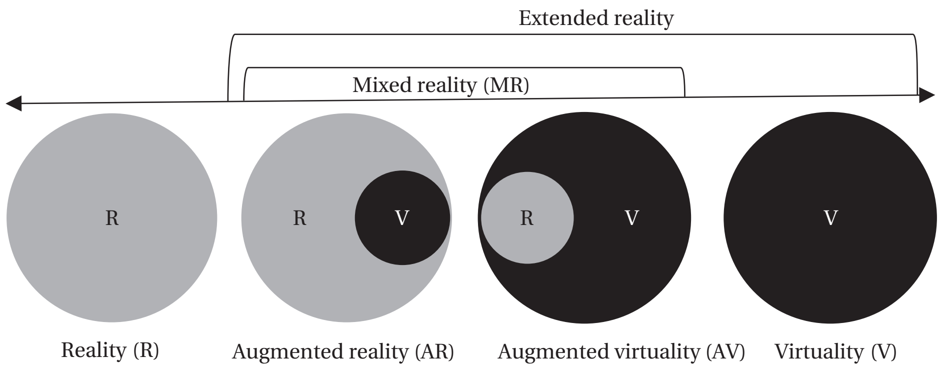

Figure 2. A system of components of the virtuality continuum
Source: developed by the authors based on P. Milgram *et al.* (1995)

Virtuality continuum reunites the kinds of objects that get incarnate in any exhibiting circumstance, the world actually existing with one end (extremum) of the continuum and the virtual world with the other. The scenario on the far left refers to settings consisting entirely of actual objects and represents the outcome of observation, for example, through a standard video display of a real scene. The second scenario involves direct viewing of the same real-world scene without the use of any specific electronic display device. The scenario on the far right describes environments composed entirely of virtual objects, such as computer-generated simulations. The most practical way of experiencing a MR environment is through a combination of real and virtual objects presented on a single display, placing it midway between the two extremes of the virtuality continuum (Milgram *et al.*, 1995).

XR is an umbrella term that describes a set of spaces of AR, VR, MR, and characterizes the technology of combining or mirroring the physical world with a "digital twin world" that is capable of interacting with it, providing users with an immersive experience of being in a virtual, augmented, or mixed environment (Casini, 2022; Tu *et al.*, 2023). VR and AR have been studied and applied in areas such as entertainment, advertising, real estate, education, technical support, and remote service, as noted by S.H.-W. Chuah (2019). Education, medicine, research, and data analysis are some of the areas where AR can be used. AR is based on applying visual collection of local or public data sent via a network to human senses. By their capacity to provide instantaneous responses to a virtual stimulus, they offer a personalised experience. As of 2025, about a third of the global AR market is in the European region. The development of 5G and edge computing (performed "at or near the data source") will increase the data transfer speed and bandwidth of user devices, and as a result, further spread of AR technology (Grand View Horizon Databooks, n.d.). MR is an area of computer research that combines AR and AV technologies, considering various options for their combination. a combination of real-world data and computer-generated data (VR), where computer-generated graphic objects are visually mixed with the real environment in real time and vice versa. MR, which combines real and virtual components, is interactive, processed in real time, recorded in three dimensions, and created using AR or augmented virtuality technologies. MR systems can be considered the most advanced computer user interface systems and the best immersive systems, and are created as optical transparent systems (usually using transparent displays) or transparent videos. Implementations of MR systems are marker systems, where the real scene is augmented with specific markers, which are detected when replacing real objects with virtual ones, or semi-markerless systems, where processing and insertion of virtual objects are done without precise markers, but usually require additional information, e.g., image and face recognition, GPS (Global Positioning System) coordinates, etc. MR is the most promising independent area of VR system development. The most characteristic aspect of the technology is the process of interchange of data and objects of the real world with those created in the virtual space. Computer-generated graphic and information elements are blended with the real world and vice versa in real time. The most important features of MR are: combination of virtual and real; interactivity; real-time interaction; three-dimensional adjustment (Sobota *et al.*, 2020).

The main purpose of a system of MR is the computerised integration of real and virtual scene coordination systems and the superimposition of real and virtual images. L.B. Rosenberg (1992) developed the first MR platform, Virtual Luminaires, at the Armstrong Laboratories of the US Air Force. This project allowed virtual objects to overlay on the real environment in the user's field of view. Currently, MR can be obtained using at least one of the following technologies: AR and/or AV. AR is a term that was first coined by researchers T.P. Caudell & D.W. Mizell (1992) and is often mistakenly considered synonymous with other components of the virtuality continuum. Therefore, AR is a technology that allows the introduction of virtual objects into the real environment. The concept of AR encompasses several dimensions: visualization, contextual actions (triggers), and visual cues (assistance). Unlike current human-computer interface technologies, which focus on making the human-computer interaction easier, AR uses computer technology to extend the human-reality interface. The concept of AR is based on the idea of creating a new generation of user interfaces by rethinking the use of input, output, and control. The key features of AR are non-trivial output and input mechanisms, specifically showing 3D models. The object view point is controlled by user natural head or device motions and is unobtrusive and efficient. This provides an opportunity to see objects immediately in the framework of their work, for instance: visualisation of furniture within the interior; exhibition of flowers within a garden; location of architecture on the plane of terrain; creation of communications within the foundation of structures; visualisation of an ultrasound scan of a patient during surgery immediately. Its popularity and widespread use decide the development and popularity of this technology branch. The first smartphone AR product was launched by M. Möhring *et al.* (2004). Currently, AR systems are already partially achieved as software products on smartphones and tablets, and work is ongoing in developing full glasses and AR lenses. It is also feasible to use fixed equipment for AR applications, such as TVs, projectors, or PC monitors. A TV screen can be used to display pre-enhanced images (e.g., sports broadcasts), while a computer monitor can display "satellite" maps, where a satellite image is overlaid with a map legend. AR technologies are also used in specialised pilot helmets in the military and civilians, which allow them to stay updated about the glass ahead without taking their eyes off the dashboard. This gives them extra seconds of focus, which is critical for aviation safety (IT-Enterprise, n.d.). In 2017, AR systems began attracting the attention of large corporations and was used as an advertising tool in retail. At the same time, the market of AR and VR games keeps expanding. By marketers, the trend of WebAR (Web-based AR) use became the main industry trend in 2020. WebAR technology is activated by triggers (QR codes or links), allowing to use a browser as a means of presenting information in AR. This approach provides high availability in everyday use because there is no need to install a special mobile application. The AR module is integrated into a web application that is supported by most modern devices, including smartphones. Industry leaders already do not think twice about the usability of AR systems, and their demand for it will continue to rise. Currently, the amount invested in WebAR is approximately USD 16.6 billion, and in 2025, it will be around USD 198 billion (Pangarkar, 2025; Dey & Jambhale, 2025).

AV is VR in which elements of the actual world are present, falls within MR and possesses a virtual world in which physical components, entities or objects are integrated with the capability to interact with the virtual world in real time. All this is attainable using some technologies: video cameras, motion-sensor cameras, and computer vision programs. As noted by A. Gruca *et al.* (2020), the first application of the AV theory was in 1997 on the Windows on the World project and utilised the Distributed Interactive Virtual Environment multi-user Internet system. The software, through the robot motion in real space, facilitated the transmission of updates of the images of the objects in question to a virtual ground model. With the help of this program, the user took into account the information received by the robot, analysed it independently, and made decisions. The program's developers planned to use it for security organisations, and further research has shown its effectiveness in construction and interpersonal communication. Projects such as the Augmented Virtual Studio for Architectural Exploration, developed by G. Bruder *et al.* (2010) at the Faculty of Computer Science at the University of Münster, and "A Layer-based 3 Architectural Collaboration", introduced by S. Schmidt *et al.* (2015), were aimed at enhancing the design of architectural structures and promoting products in the market. The developers of the Augmented Virtual Studio for Architectural Exploration project proposed exploring virtual space using a VR helmet. With the assistance of immersive VR systems (Cave Automatic Virtual Environment), the users are able to experience virtual scenes with mobility. Immersive virtual environments provide a shared platform for communication and exchange of architectural design concepts and have tremendous potential to contribute to the development of architectural models. The three-dimensional architectural scenes can be explored by the users through immersive navigation, which helps them get an overall view of the project. The authors of the project "A Layer-based 3D Virtual Environment for Architectural Collaboration" proposed using virtual environment in which customers could take part to perform collaborative navigation in architectural models. Based on visualisation technique with a layer blending the software overlays plan drawings of floor over each other in such manner that the overlaid effect created will resemble visual impression of plan in three-dimensions with out the real use of actual 3D technology. The interface of the program uses two images of the same structure. The interface allows the architect to indicate specific points on the 3D mapping of the project, and other users can study this area on a two-dimensional plan. The virtual building is shown in this mode on two different planes of the L-shaped design system. VR is a virtual three-dimensional space generated by technological devices and through interaction with a person using his or her senses (sight, hearing, touch, etc.). The basic goal of VR technologies is to make the perceived visible digital world by the human brain appear like reality (IT-Enterprise, n.d.). In its widest definition, VR is an imitation world which replaces audiovisual data from the surroundings with data generated by a program, to be differentiated from AR, wherein data from the real world are only partly augmented by virtual additions. According to the conclusions of V. Volynets (2021), there are two main forms of VR: modeled and interactive, and although they vary to a certain extent, they deal with such features as interactive activities of hardware-simulated objects, and the impact of their images on the human mind. That is, the virtual world cannot be identified with a group of microchips, because this phenomenon has a psychological component. VR is also defined as a technology based on communication between a person and an artificial digital model, and on methods of visualisation of the digital world, its manipulations and transformations.

Depending on the degree of user interaction with VR models, VR can be divided into three categories: passive reality, supervised interactive reality, and direct VR. On this account, the main goal of VR is real simulation in the virtual world (at least physically), but such an environment itself is simulated by computers, i.e., created by a person in a virtual world. The basic distinction of VR compared to AR is that the latter mixes up digital aspects with the surrounding environment, while human-influenced VR systems, and AR by the overall external world readable by hardware. The main requirements and roles in VR system design are realism, interactivity, openness to cognition, and presence simulation. Realism involves creating a solid degree of believability in the digital imitation one is experiencing. Interactivity ensures active involvement of the user in interaction and manipulation within the virtual space. Openness to cognition refers to the ability to experience and perceive virtual spaces in high definition. And lastly, presence simulation works towards generating maximum sensory impact by both the involvement of the user's brain and body in simulated interaction. A complete VR system must possess a series of compulsory components. It must contain polysensory devices that connect the user to the virtual environment such as sensor shoes, head-mounted displays, smell masks, motion trackers, sensor gloves, and sensor suits. The system must also have a hardware and software core that can talk to these sensors and to manipulation devices like pedals, levers, microphones, headphones, and joysticks. The system must also include application software that determines the dynamics, structure, and interaction laws of the virtual environment. Geometry provides the language for the physical properties of virtual objects, and the platform as a whole provides dynamic feedback to facilitate an interactive and responsive interface. Regardless of the hardware component, VR systems are directly related to immersiveness, an effect that, despite its popularity, is not sufficiently defined in terms of terminology. The phenomenon of immersiveness was borrowed from the film industry, where it is used as a technique for staging and filming a scene to create the effect of immersion in the atmosphere desired by the author with the characteristic features of a particular movie universe. In spite of typical stereotypes and the corresponding associations of VR technologies with entertainment, nowadays their sphere of application is broader and more diverse. VR facilitates the learning process in education by increasing the degree of user involvement and interest. In education, VR mimics dangerous, costly, or professional conditions such as piloting an airplane, parachuting, or driving, where students can gain practical experience in a safe virtual environment. In scientific research, VR enables the recreation of molecular, atomic, macro-, and microcosmic worlds, where researchers can manipulate and observe individual components in real time. In the medical field, it allows for the simulation of complex surgery, allowing surgeons to practice and master their skills without the need to utilize real patients or physical models. In architecture and design, VR allows for the creation and modification of virtual 3D models of various types and purpose, offering an unyielding visualisation and prototyping tool. Finally, with VR in virtual tourism, it is possible to travel virtually via simulated environments that replicate actual locations, opening access to exploration and cultural immersion.

Comparison and assessment of the prospects for XR, MR, AR, AV, and VR technologies. All components of the virtuality continuum created in this reseach are new and necessary when conducting research, but from the point of view of technological advancement and investment possibilities, they basically have alternative values since their use depends on a wide range of factors: the degree of development of software and hardware components (power sources, reading sensors, output devices, etc.), areas of application, and accessibility of special alternatives for visually impaired individuals and individuals with disabilities. Below are the resultant estimates derived from open-source statistical analysis, considering hardware development dynamics, market conditions, and price trends (Fig. 3). Autonomy describes the ability of a device to operate without the use of outside power sources, trackers, cameras, or cloud rendering. AR and XR both received a score of 4 because most glasses are independent but sometimes must be plugged into a smartphone. VR received a score of 3 because only a few models are independent, MR and AV scores are the lowest (Table 2).

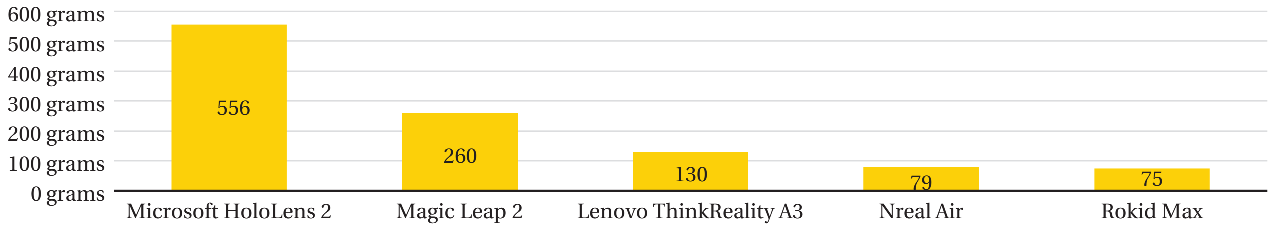

Figure 3. Comparison of AR devices by weight

Source: M. Dey & R. Jambhale (2025)

Mobility determines the extent to which a device can be transferred from set conditions without loss of functionality. A good form of light AR and XR headsets benefit the most. VR is in the middle because the majority of headsets are mounted on a PC. MR and AV receive the least because they are a difficult adaptation in the outdoor environment. Figure 4 illustrated the relative affordability of various AR-related devices, showing how differences in cost influenced their accessibility scores. Affordability was assessed based on the average cost of each technology. AR received only 2 points due to the dominance of devices such as the HoloLens 2 ($3,500) and similar models. XR (3 points) encompassed both budget and premium segments of AR/VR. The Meta Quest 2 ($299) scored lower than VR, which received 4 points. AV achieved 4 points due to its effective utilisation of existing displays and low-cost headsets. MR had the highest average cost, resulting in a score of only 1 point. Figure 5 depicted the projected growth of the global XR market, demonstrating how differences in investor interest affected the market potential of XR, VR, AR, MR, and AV technologies.

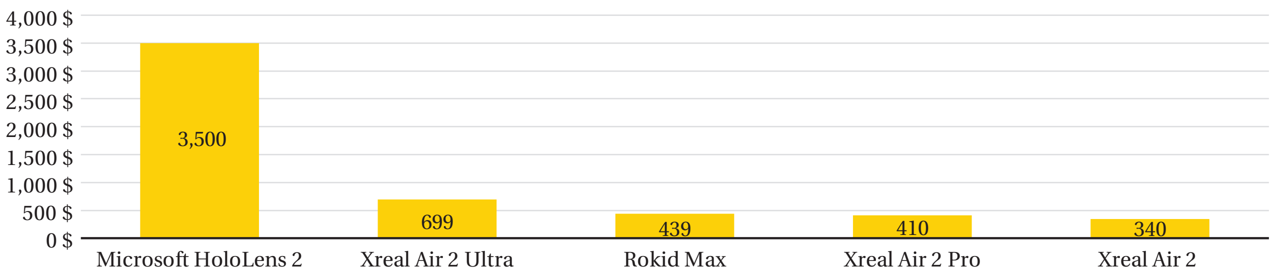

Figure 4. Comparison of AR devices by price

Source: M. Dey & R. Jambhale (2025)

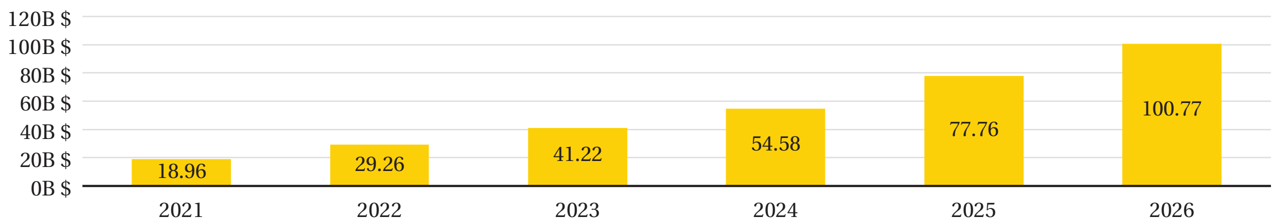

Figure 5. XR market size worldwide

Source: M. Dey & R. Jambhale (2025)

Market growth is forecasted based on market dynamics. For XR, growth is projected from $18.96 billion in 2021 to $100.77 billion in 2026 (Dey & Jambhale, 2025). It is noted that XR retains 5 points, VR and AR retain 4, MR retains 3, while AV retains only 2 due to limited investor interest. Figure 6 illustrated the shipment volumes of AR and VR devices across consumer and commercial markets, showing adoption levels and highlighting the relative popularity and growth of XR, VR, AR, MR, and AV technologies.

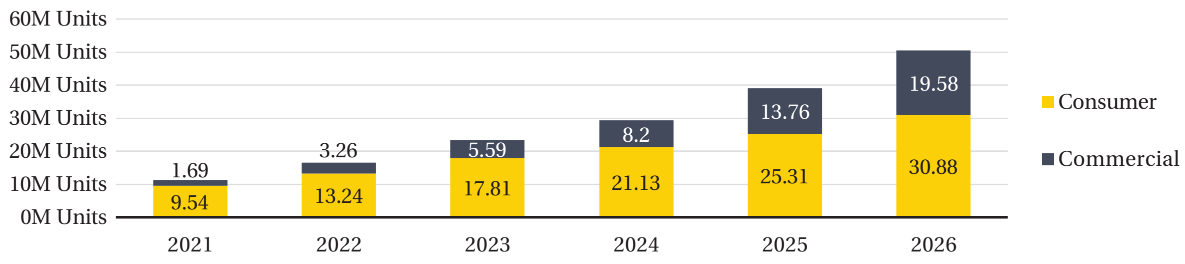

Figure 6. AR and VR devices shipments for consumer and commercial markets
Source: M. Dey & R. Jambhale (2025)

Popularity is quantified in terms of technology adoption among corporate and private consumers and is based on a chart representing the number of devices in millions. For example, VR and XR (4 points) are the most prevalent devices among consumers with XR being the fastest-growing device. AR is 3 points for widespread B2B usage but lower for B2C, and MR and AV are 2 points. The technological maturity of XR, AR, VR, MR, and AV was shown in Figure 7, with XR and VR rated highly, AR moderately, and MR and AV lower due to technical complexity and limited adoption.

Applicability is measured by how many and what kinds of industries and potential applications there are. AR and XR (5 points) are used everywhere, for example. VR (3 points) has most of its uses in entertainment and education. MR has industrial simulations that amount to 4 points, whereas AV has only 2 points because of the few number of application scenarios. The graph in Figure 7 indicates the huge lead of XR technologies over their competitors and the slim opportunity for two areas at once – MR and AV. The technological maturity dictates stability, standardisation, vendor support, and mass-readiness. For example, VR (4 points) offers several headsets, platforms, and SDKs. AR and XR (3 points) are developing but not yet standardised. MR and AV (2 points) remain unstable and platform-dependent (Table 3).

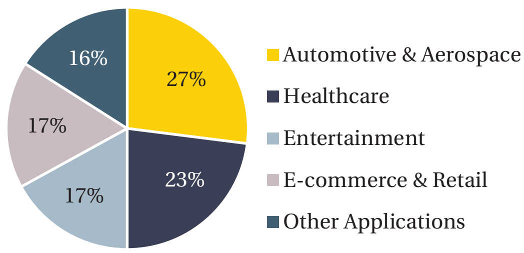

Figure 7. Global MR market share by application
Source: T. Pangarkar (2025)

Table 3. Comparison of the components of the virtuality continuum

Attribute type	Virtual reality (VR)	AR (AR)	Extended reality (XR)	Mixed reality (MR)	Augmented virtuality (AV)
Mobility	2	4	4	3	3
Autonomy	3	4	4	3	2
Affordability	4	2	3	1	4
Popularity	4	3	4	2	2
Market growth	4	4	5	3	2
Applicability	3	5	5	4	2
Technological maturity	4	3	3	2	2

Source: developed by the authors based on M. Dey & R. Jambhale (2025) and T. Pangarkar (2025)

The results attained in Table 3 become understandable due to the fact that XR combines the best qualities of VR, AR, and AV technologies, which cannot attain such results individually, while MR, in turn, has only common features by half, which are not only advantages but also disadvantages. The narrow range of AV advancements and the costly and time-consuming nature of their implementation have the lowest likelihoods of their leadership in the market.

Table 4. Prospect index calculation

Technology type	Total score	Perspective index
Virtual reality (VR)	24	3.43
AR (AR)	25	3.57
Extended reality (XR)	28	4.00
Mixed reality (MR)	18	2.57
Augmented virtuality (AV)	17	2.43

Source: developed by the authors based on M. Dey & R. Jambhale (2025) and T. Pangarkar (2025)

The results presented in Tables 3 and 4, are explained in the light of the technological maturity level, hardware capacity, and market availability of each of the technologies in the virtuality continuum. For example, XR technology received the highest promise index (4.00) due to the combination of AR, VR, and AV benefits, which makes it simple to adjust to the technical implementation of various tasks. Figure 8 illustrated the comparative evaluation of the development potential of technologies across the virtuality continuum, showing their relative positions according to both direct and indirect assessment criteria.

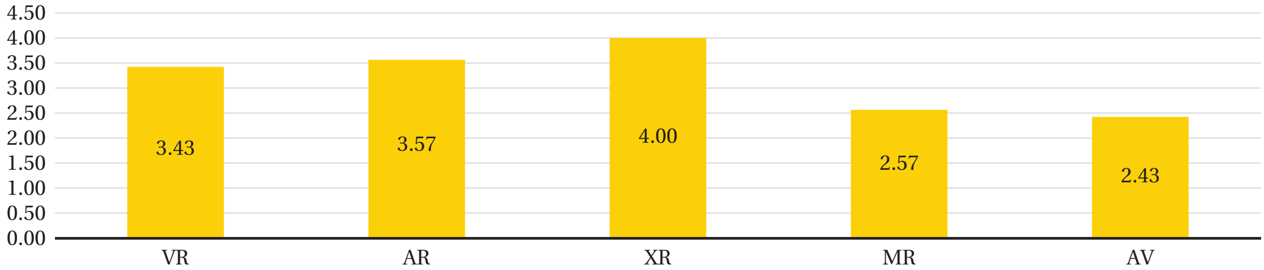

Figure 8. Technology prospects chart

Source: developed by the authors based on M. Dey & R. Jambhale (2025) and T. Pangarkar (2025)

In Figure 8, AV was assigned the lowest index due to its narrow applicability scope and challenging technical implementation, which in turn affects both direct evaluation criteria (autonomy, mobility, applicability, affordability) and indirect ones (popularity, technological maturity, market growth). It is required to mention that the derived outcomes are estimated only on the basis of open information and do not take into account the factors of development of individual technologies, which may significantly affect the corresponding prospect indicators. Despite this, there is significant variation in the results of the comparisons and, with all these criteria being taken into account, suggests a very high degree of accuracy in their calculation of each element of the virtuality continuum's potential for development. The proposed model of comparative analysis in this work has high accuracy and completeness, as confirmed by the findings of O. Kanarskyi *et al.* (2022), who underlined that multi-criteria evaluation metrics need to be developed for AR systems in a systematic way. Contrary to R.T. Azuma (1997), where AR technologies were considered from the point of view of only hardware, this work provides a more structured estimation model, combining market dynamics and technological readiness. Similarly, while M. Casini (2022) and C. Coupry *et al.* (2021) underlined the role of XR technologies in smart building maintenance, their studies also had several methodological limitations in conducting a quantitative assessment of technological maturity. This work puts together both quantitative and qualitative approaches: it combines the prospect index with contextual interpretation, which provides more methodological robustness to the comparison. Conclusions also partially coincide with the results of E. O'Hara *et al.* (2024), who underlined the ergonomic and usability aspects of AR implementation; however, the accent is different: whereas their study was focused on user experience and cognitive interaction, the present model covers technological and economic parameters. By contrast, X. Guo *et al.* (2025) focused on the problems of VR/XR system security and privacy. Their results, while demonstrating more pronounced barriers to adoption, identify wider opportunities for XR, VR, and AR from the current research based on market indicators. The proposed solution, therefore, extends the discussion introduced by J. Hu (2024) and T. Blackman & D. Harley (2024) with respect to spatial computing devices, as it provides a structured comparative basis for assessing their developmental readiness. The proposed approach effectively addresses the questions posed in Section 2, i.e., the lack of a unified classification of XR, AR, MR, VR, and AV technologies, and the necessity to evaluate their potential individually. Thanks to the conceptual scheme given in Figure 2 and the systematisation of characteristics shown in Tables 1 and 2, a justified set of concepts and criteria has been formed for selecting the most suitable technology for specific applications. However, this research has some limitations: firstly, the comparison and analysis have been made based on open statistical sources without hardware testing by experiments, which partially affects the accuracy of the results; secondly, the chosen assessment system is expert-analytical and doesn't take into account the influence of the level of immersion in relation to changes in the user's psychophysiological state.

Conclusions

As a result of the taxonomic analysis of the components of the virtuality continuum, a clear terminological system for defining XR, MR, AR, AV, and VR technologies was established. Unlike previous approaches, where terms often overlap or are ambiguously distinguished, the proposed model provides a coherent hierarchy and an explicit conceptual framework. In particular, AR was identified as a technology that supplements the real world with virtual objects, whereas AV supplements the virtual world with real-world objects, and VR represents a fully virtual environment. XR, as a combination of AR, VR, and AV, and MR, as an intersection of AR and AV, were considered separately, thereby eliminating terminological uncertainty. A comparative analysis of above technologies was conducted based on seven criteria – immersiveness, autonomy, mobility, accessibility, popularity, market growth, and technological maturity, which enabled an evaluation of their effectiveness. XR achieved the highest promise index (4.00), encompassing the advantages of AR, VR, and AV. AR scored highest in mobility (5/5) and autonomy (4/5), making it particularly suitable for mobile and autonomous applications. VR demonstrated high immersiveness (5/5) and accessibility (4/5), consistent with its commercial success. AV and MR received lower scores (2.43 and 2.57, respectively), with MR constrained by technical complexity and AV by a limited scope of application. Unlike most previous studies, which primarily provided qualitative assessments, this research conducted a comparative evaluation that allows for the identification of optimal and promising technologies for specific tasks. Future research is expected to expand the high-level model by integrating user interaction indicators, sensory inputs, and cognitive load measures to derive more nuanced conclusions regarding the efficacy of XR, AR, VR, MR, and AV technologies in real-world applications.

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Conflict of Interest

None.

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Таксономічний аналіз складових континууму віртуальності

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Анотація. Метою дослідження було формування універсальної моделі континууму віртуальності для подальшого групування та впорядкування відповідних технологій, а також оцінки їхнього потенціалу для подальших досліджень. Об'єктом дослідження був континуум віртуальності як концептуальна модель взаємодії реального світу з віртуальним середовищем. Проблема, що вирішувалася, полягала у відсутності чіткої термінологічної бази та критеріїв класифікації складових віртуальності, що ускладнює їх інтеграцію в науку, бізнес та повсякденне життя. Для вирішення проблеми в статті проведено таксономічний аналіз складових континууму, а саме: розширеної реальності (XR), змішаної реальності (MR), віртуальної реальності (VR), доповненої реальності (AR) та доповненої віртуальності (AV). Запропоновано узагальнену концептуальну схему, яка демонструє їх взаємозв'язки, а також спільні та відмінні риси. За результатами дослідження, найвищий показник перспективності отримала технологія XR (4,00/5) завдяки поєднанню переваг VR, AR і AV. Високу мобільність і автономність продемонструвала AR (3,57/5), що робить її зручною для мобільних застосунків. VR (3,43/5) відзначилась високим рівнем популярності та доступністю обладнання. MR (2,57/5) отримала нижчу оцінку через складність технічної реалізації, а AV (2,43/5) – через обмежену сферу застосування та високу вартість впровадження. Результати ґрунтуються на структурованих алгоритмах для класифікації об'єктів, а також їх детальному порівнянні за сімома критеріями: мобільність, автономність, доступність за ціною, популярність, зростання ринку, застосовність, технологічна зрілість. Особливістю підходу було поєднання розбору понятійної бази з оглядом практичних прикладів впровадження технологій у різноманітних галузях, а також числовим аналізом на основі статистики з відкритих джерел. Практична цінність результатів полягає у можливості їх застосування під час розроблення інтерфейсів користувача, проєктування новітніх засобів інформаційних технологій та моделювання віртуальних середовищ. Отримані показники зумовлені високою точністю аналізу, що є прямо пропорційною кількості розглянутих характеристик

Ключові слова: віртуальні технології; індекс перспективності; технологічна зрілість; ринкові показники; мобільність