Journal of Computer Science

Research Paper

Evaluating Barriers to the Adoption of Augmented Reality-based Applications in Education System: DEMATEL Approach

Monika Nijhawan[1,2], Nidhi Sindhwani[1], Sarvesh Tanwar[1], Shishir Kumar[3]

[1]*Amity Institute of Information Technology, Amity University, Noida, Uttar Pradesh, India*
[2]*New Delhi Institute of Management, New Delhi, India*
[3]*Department of Computer Science, Babasaheb Bhimrao Ambedkar Central University, Lucknow, Uttar Pradesh, India*

Article history
Received: 10 March 2025
Revised: 16 May 2025
Accepted: 11 June 2025

*Corresponding Author:
Sarvesh Tanwar
Amity Institute of Information Technology, Amity University, Noida, Uttar Pradesh, India
Email: dr.sarveshtanwar@gmail.com

Abstract: Augmented Reality (AR) is an emerging technology that enhances user perception by overlaying virtual information onto the physical world. In educational contexts, AR integration has demonstrated potential to improve learning engagement, motivation, and conceptual understanding among students. However, teachers face numerous challenges when incorporating AR technologies into classroom instruction, including technical difficulties stemming from inadequate training, resistance to technology adoption, and curriculum misalignment with available AR tools. This study systematically identifies and analyzes barriers impeding the successful implementation of AR applications in K-12 education. Following a comprehensive literature review, an expert committee validated and refined the identified barriers through pilot testing. We employ the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method (a Multi-Criteria Decision-Making (MCDM) approach) to quantify the relative importance of each barrier and establish cause-and-effect relationships among them. Results reveal that teacher adaptability toward technology constitutes the most critical barrier to AR implementation, followed by the need for effective pedagogical strategies. DEMATEL analysis further demonstrates that two causal factors, allocating sufficient funding and developing effective pedagogy, significantly influence four effect factors: content quality, teacher adaptability, interface design, and technical infrastructure. Specifically, the findings indicate that investing in teacher professional development, ensuring adequate financial resources, and integrating pedagogically sound AR applications can substantially reduce implementation barriers and maximize educational benefits. Based on these results, we recommend that educational institutions prioritize teacher training programs, allocate dedicated budgets for AR infrastructure, and develop curriculum-aligned AR content to facilitate successful technology integration. This study contributes to the understanding of AR adoption barriers in education and provides actionable insights for policymakers, administrators, and educators seeking to enhance teaching quality and better prepare students for technologically advanced futures.

Keywords: Augmented Reality; Educational Technology; Multi-Criteria Decision Making; DEMATEL; Technology Adoption Barriers; Teacher Training; Pedagogical Innovation; K-12 Education

Introduction

Technology-enhanced learning has consistently demonstrated benefits for student comprehension and conceptual understanding. Augmented Reality (AR) represents a significant advancement in educational technology, bridging the gap between virtual and physical environments to deliver information in an immersive, interactive manner (Shankar et al., 2021; Lee, 2012). As illustrated in Figure 1, AR exists on a reality-virtuality continuum, with real-world objects (such as photographs and QR codes) at one end and fully computer-generated virtual environments at the other. AR overlays digital information onto the physical world, enhancing real-world perception through supplementary virtual content that expands the knowledge continuum.

AR, alongside Virtual Reality (VR), constitutes a core technology of Industry 4.0, complementing other transformative technologies including the Internet of Things (IoT), Cyber-Physical Systems (CPS), collaborative robotics, big data analytics, 3D printing, and Artificial Intelligence (AI) (Lee, 2012). Beyond education, AR has demonstrated growing utility across diverse sectors such as manufacturing, retail, aviation, simulation training, and hands-on project-based learning (Garzón & Acevedo, 2024). The primary AR implementation techniques include marker-based tracking, markerless tracking, and location-based (geographic) AR (Wedel et al., 2020).

In educational contexts, AR offers unique affordances for visualizing abstract concepts that are difficult to convey through traditional instruction. Applications span multiple disciplines, including biological anatomy visualization, molecular structures in chemistry, three-dimensional geometric concepts, and interactive storytelling (Tseng, 2020). Educational AR applications can be categorized into four primary types: (A) AR-enhanced textbooks and reading materials, (B) educational games incorporating AR elements, (C) discovery-based learning applications supporting inquiry learning, and (D) AR projects designed for skill-based and experiential learning (Fitria, 2023). Existing research demonstrates that AR integration enhances subject comprehension, promotes interactive learning experiences, and improves creativity, critical thinking, memory retention, student engagement, and collaboration compared to conventional classroom instruction methods.

Despite these documented benefits, educators face significant challenges when implementing AR technologies, particularly in helping young learners grasp complex concepts. While AR has the potential to facilitate understanding, several barriers impede its widespread adoption in educational settings. Prior research has identified key implementation challenges, including technical infrastructure limitations (Shankar et al., 2021; Wedel et al., 2020; Sitopu et al., 2024), insufficient funding for AR technologies and equipment (Oke et al., 2022; Bistaman et al., 2018), parental resistance and concerns about technology use (Oke et al., 2022), teacher resistance to adopting new pedagogical technologies (Shankar et al., 2021; Sitopu et al., 2024), and limited educational scope in existing AR applications (Bistaman et al., 2018).

While previous studies have documented various challenges in AR adoption within education, no existing research has systematically analyzed the relative importance of these barriers or established causal relationships among them using rigorous multi-criteria decision-making methodologies. This gap is particularly significant given that understanding interdependencies among barriers is essential for developing effective intervention strategies. Game-based learning approaches, which leverage enjoyment and intrinsic motivation, have shown promise in enhancing student interest and learning outcomes (Sırakaya & Alsancak Sırakaya, 2022). However, successful implementation requires careful consideration of the fundamental factors that influence technology adoption in educational institutions.

Contemporary educational policies, such as India's New Education Policy (NEP 2020), emphasize experiential learning and advocate for integrating innovative pedagogies and technological advancements into teaching practices. Aligning with this policy direction, there is an urgent need to identify and address the key barriers that influence successful AR implementation in the education sector. This study addresses this gap by employing the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method to: (1) identify and validate critical barriers to AR adoption in education through comprehensive literature review and expert validation, (2) quantify the relative importance of each barrier, and (3) establish cause-and-effect relationships among barriers to inform targeted intervention strategies.

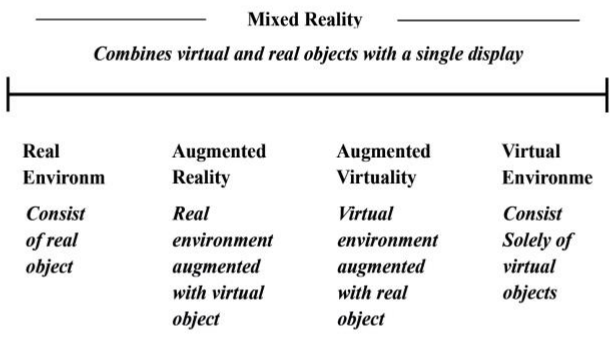

Fig. 1. Milgram's Continuum about Physical World, Augmented Reality, Augmented Virtuality, and Virtual Reality (1994) (Fitria, 2023)

Literature Review

This literature review examines the current state of Augmented Reality (AR) integration in education, focusing on documented benefits, implementation challenges, and barriers to adoption. By synthesizing relevant research across multiple contexts and educational levels, we establish the theoretical foundation for investigating causal relationships among AR adoption barriers using multi-criteria decision-making methodologies.

Augmented Reality in Education: Benefits and Applications

AR technology has demonstrated significant potential to transform educational practices by overlaying digital information onto physical environments, creating immersive and interactive learning experiences (Van Krevelen & Poelman, 2010). Research consistently shows that AR enhances student motivation, engagement, conceptual understanding, memory retention, and collaborative learning compared to traditional instructional methods (Wu et al., 2013; Tseng, 2020; Lai et al., 2022).

Educational AR applications span diverse disciplines and formats. In STEM education, AR facilitates visualization of abstract concepts such as molecular structures in chemistry, anatomical systems in biology, and three-dimensional geometric relationships in mathematics (Pellas et al., 2019; Sitopu et al., 2024). Yavuz et al. (2021) found that marker-based AR applications particularly enhance K-12 STEM learning through improved engagement and conceptual understanding. Beyond traditional academic subjects, AR supports language learning through spelling games, vocabulary building, and contextual word associations (Zander et al., 2023), while Iqbal et al. (2022) demonstrated that mobile AR (MAR) multiplayer games effectively develop social skills including empathy, communication, and collaboration among elementary students.

Fitria (2023) categorizes educational AR applications into four primary types: (1) AR-enhanced textbooks and reading materials, (2) educational games incorporating AR elements, (3) discovery-based learning applications supporting inquiry learning, and (4) AR projects designed for skill-based experiential learning. This categorization reflects AR's versatility across formal classroom instruction, outdoor education, special education, and collaborative learning contexts. Notably, AR has shown particular promise for students with special needs, improving motivation, engagement, and academic achievement when implemented with adequate teacher preparation (Matsika & Zhou, 2021; Fernández-Batanero et al., 2022).

The integration of AR with game-based learning (ARGBL) leverages intrinsic motivation through enjoyable, interactive experiences (Sırakaya & Alsancak Sırakaya, 2022). Hamutoglu and Basarmak (2020) found that ARGBL enhances student learning, motivation, and engagement, proving particularly effective in social sciences and STEM fields. Recent developments combining AR with artificial intelligence and learning analytics enable personalized learning experiences, real-time progress monitoring, and targeted interventions addressing individual student weaknesses (Mohammed, 2024; Criollo-C et al., 2024).

Implementation Challenges and Adoption Barriers

Despite documented benefits, AR adoption in education faces substantial barriers that impede widespread implementation. Existing research identifies six primary barrier categories that affect successful AR integration.

Teacher Adaptability and Technology Resistance

Teacher resistance constitutes a critical barrier to AR adoption. Educators often prefer familiar traditional methods and express concerns about professional competency, job security, and the time investment required for technology integration (Oke et al., 2022; Shankar et al., 2021). Yılmaz et al. (2023) found that teachers report insufficient confidence in their AR skills and struggle to find time within demanding schedules to explore AR technologies, develop AR-based lessons, and integrate them into existing curricula. This resistance is compounded when AR's student-centered pedagogy conflicts with conventional teacher-centered instructional approaches (Lai et al., 2022).

Financial Constraints and Resource Limitations

Cost represents a significant barrier at multiple levels. AR hardware (tablets, smartphones, AR glasses) and implementation infrastructure require substantial initial investment (Shankar et al., 2021; Wedel et al., 2020; Matsika & Zhou, 2021). Educational institutions, particularly those with limited budgets, face challenges providing AR devices to all students and maintaining equipment over time. Beyond hardware costs, developing or purchasing curriculum-aligned AR content requires additional financial resources that many schools cannot allocate (Oke et al., 2022; Perifanou et al., 2022). This financial burden is particularly acute in developing countries and underserved regions where basic educational infrastructure may already be inadequate (Laferrière et al., 2013).

Content Quality and Availability

The shortage of high-quality, curriculum-aligned AR educational content across multiple disciplines and languages limits effective implementation (Yılmaz et al., 2023). Teachers require compelling, pedagogically sound content to justify AR investment, yet many report difficulty accessing appropriate materials (Tseng, 2020;

Oke et al., 2022). Hamutoglu and Basarmak (2020) note that teachers often must create supplementary resources to accompany ARGBL experiences, adding to their workload. Furthermore, inflexible course structures and complex information flow across devices create additional content-related challenges (Lai et al., 2022).

User Interface and Design Considerations

AR applications must feature age-appropriate, intuitive interfaces tailored to students' developmental levels and technical proficiency (Bistaman et al., 2018; Perifanou et al., 2022). Poorly designed interfaces create usability barriers that impede learning rather than facilitate it. Van Krevelen and Poelman (2010) identified technical challenges including display resolution, field of view, ergonomics, and power consumption that affect user experience. For AR to become seamlessly integrated into daily educational practice, interface design must prioritize simplicity, accessibility, and student-centered usability.

Pedagogical Integration Challenges

Effective AR implementation requires more than technological competence, it demands pedagogical innovation and instructional redesign (Lampropoulos et al., 2022). Research indicates insufficient established pedagogical frameworks for AR-enhanced personalized and experiential learning (Fitria, 2023; Alalwan et al., 2020). Teachers need clear AR-specific instructional objectives, evidence-based teaching strategies, and assessment methods appropriate for AR environments. Lampropoulos et al. (2022) found that AR's learning impact varies significantly based on instructional approach, with collaborative learning methodologies showing the greatest effect sizes. However, many studies focus primarily on technological aspects while neglecting pedagogical considerations, leaving educators without adequate guidance for effective implementation. Additionally, rigid curricula and time constraints limit opportunities to integrate AR's innovative teaching techniques (Lai et al., 2022; Hamutoglu & Basarmak, 2020).

Technical Infrastructure and Connectivity Issues

Reliable technical infrastructure is fundamental to AR implementation. AR experiences require robust Wi-Fi connectivity, which may necessitate network infrastructure upgrades in many schools (Oke et al., 2022; Tseng, 2020). Technical challenges include accurate object and surface tracking, calibration issues, environmental factors (lighting variations, physical obstructions), and device compatibility concerns (Shankar et al., 2021; Lai et al., 2022). Hardware limitations of older mobile devices may prevent some students from participating in MAR activities, creating equity issues (Alalwan et al., 2020). Geographic disparities in internet access further exacerbate these challenges, particularly in rural and underserved areas (Laferrière et al., 2013).

Context-Specific Insights

Several studies provide valuable context-specific insights. Wedel et al. (2020) examined mixed reality learning with Microsoft HoloLens across 223 students at multiple educational levels, identifying presence, interactivity, immersion, and novelty as factors influencing positive learning states, while noting inflexibility, accessibility problems, and device complexity as significant drawbacks. John et al. (2022) found that AR games enhance elementary school collaboration and socialization, though successful implementation depends heavily on teacher preparation. Research on special populations reveals that AR benefits young children (ages 4-5) through improved attention, reasoning, and conceptual abilities (Nincarean et al., 2013; Fernández-Batanero et al., 2022).

The COVID-19 pandemic highlighted AR's potential for remote learning while simultaneously exposing digital divides and access inequalities (López-Faican & Jaen, 2020). Fitria (2023) emphasized the importance of touchless hand interaction and remote learning pedagogy for teaching children during pandemic conditions. However, Alalwan et al. (2020) documented significant challenges in Latin American higher education institutions, including limited training, infrastructure deficiencies, internet access issues, and resource constraints.

Research Gaps and Study Justification

While existing literature extensively documents AR's educational benefits and identifies various implementation barriers, three critical gaps remain unaddressed. First, no studies have systematically quantified the relative importance of different barriers to prioritize intervention strategies effectively. Second, research lacks rigorous analysis of causal relationships and interdependencies among barriers, which is essential for understanding how addressing one barrier might influence others. Third, existing studies employ primarily qualitative or single-method approaches, lacking the multi-criteria analytical frameworks necessary to support evidence-based policy and implementation decisions.

Several researchers explicitly call for additional investigation. Sırakaya and Alsancak Sırakaya (2020) recommend gathering end-user feedback, ensuring hardware-software compatibility, providing pedagogical guidance and adequate training, and addressing usability issues before implementing MAR applications. Akçayır and Akçayır (2017) emphasize the need for comprehensive assessment, stakeholder participation in educational experience design, and sufficient training for all participants. Perifanou et al. (2022) urge further research to develop best practices for AR utilization in education.

This study addresses these gaps by employing the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method, a rigorous multi-criteria decision-making approach, to: (1) systematically identify and validate critical AR adoption barriers through comprehensive literature review and expert consultation, (2) quantify the relative importance and influence intensity of each barrier, and (3) establish cause-and-effect relationships among barriers to inform targeted, evidence-based intervention strategies. By providing both theoretical insights into barrier interdependencies and practical guidance for policymakers and educational administrators, this research contributes to the development of more effective AR implementation frameworks.

Table 1. Summary of AR Adoption Barriers in Education

Barrier Category	Key Issues	Supporting Studies
Teacher Adaptability	Resistance to change; insufficient confidence; time constraints; fear of job loss	*(Shankar et al., 2021; Tseng, 2020; Wedel et al., 2020; Shieh et al., 2010; Yılmaz et al., 2023; Oke et al., 2022; Sitopu et al., 2024; Alalwan et al., 2020; Yavuz et al., 2021; Laferrière et al., 2013*
Financial Constraints	High hardware costs; infrastructure investment; content development expenses; limited school budgets	*(Shankar et al., 2021; Tseng, 2020; Yılmaz et al., 2023; Oke et al., 2022; Fitria, 2023; Perifanou et al., 2022; Matsika & Zhou, 2021)*
Content Quality	Shortage of curriculum-aligned materials; limited multilingual resources; inflexible course structures	*(Tseng, 2020; Yılmaz et al., 2023; Oke et al., 2022; Lai et al., 2022; Hamutoğlu & Başarmak, 2020; Bistaman et al., 2018; Yavuz et al., 2021; Zander et al., 2023)*
Interface Design	Age-inappropriate interfaces; complex usability; ergonomic challenges	*(Bistaman et al., 2018; Tzeng et al., 2007; Shieh et al., 2010)*
Pedagogical Integration	Lack of established frameworks; insufficient instructional guidance; curriculum time constraints	*(Shieh et al., 2010; Yılmaz et al., 2023; Oke et al., 2022; Fitria, 2023; Lai et al., 2022; Hamutoğlu & Başarmak, 2020; López-Faican & Jaen, 2020; Criollo-C et al., 2024; Lampropoulos et al., 2022)*
Technical Infrastructure	Connectivity issues; tracking accuracy; device compatibility; digital divide	*(Shankar et al., 2021; Shankar et al., 2021; Wedel et al., 2020; Shieh et al., 2010; Yılmaz et al., 2023; Oke et al., 2022; Fitria, 2023; Lai et al., 2022; Sitopu et al., 2024; Perifanou et al., 2022; Alalwan et al., 2020; Matsika & Zhou, 2021; Yavuz et al., 2021; Laferrière et al., 2013; Fan et al., 2020; Garzón et al., 2020)*

Materials and Methods

This study employs a quantitative analytical framework to systematically evaluate the impediments to Augmented Reality (AR) adoption in the education sector.

Research Framework and Objectives

Despite the potential of AR, its integration into schools is hindered by multifaceted factors, including the lack of technical support (e.g., Wi-Fi connectivity, digital devices), ineffective pedagogy, content design limitations, and funding constraints. To address the need for a structured analysis of these challenges, this study pursues two primary research objectives:

- **RQ1:** To identify and analyze the specific barriers influencing the adoption of AR in education using the Decision-Making Trial and Evaluation Laboratory (DEMATEL) technique.
- **RQ2:** To prioritize these barriers and map their causal interrelationships to facilitate the

development of successful implementation strategies.

Methodology and Model Selection

To achieve these objectives, the study utilizes a primary survey to gather expert data regarding the identified barriers. The **DEMATEL** method was selected as the core analytical tool for this research due to its effectiveness in analyzing complex structural relationships. Unlike simple ranking methods, DEMATEL allows for the quantitative analysis of the causal dependencies between barriers, visualizing them as a cause-and-effect network to guide decision-making.

DEMATEL is a Multi-Criteria Decision Making (MCDM) technique used for analyzing and solving complex decision-making problems. It gives relevance to identified factors and creates causal and effect relationships between various factors. There are many MCDM techniques like AHP, DEMATEL, ANP, and Fuzzy Logic. DEMATEL is the best technique over other MCDM techniques because its helps in finding the complex relationships between the factors which might be difficult with other MCDM methods. Previous studies utilized this method for different enablers and barriers to examine the cause-and-effect relationship and influence level of one factor on the other in (Shieh et al., 2010; Aydoğdu, 2022; Fitria, 2022c; Van Krevelen & Poelman, 2010; Alalwan et al., 2020; Wu, 2008; Sumrit & Anuntavoranich, 2013; Behl et al., 2019; Kazancoglu & Ozkan-Ozen, 2018; Yang et al., 2013; (Nayak & D'Souza, 2019).This further justifies the relevance of DEMATEL approach for this study. Previous research in (Yang et al., 2013) interviewed 11 experts on industrial revolution, 8 experts to analyze the critical factors for supply chain management in (Kazancoglu & Ozkan-Ozen, 2018) and 6 experts to analyze the causal relationship on technological innovation factors in Thai based firms in (Sumrit & Anuntavoranich, 2013). This justifies sample size of research experts for this study. Based on convenience, experts were selected. Later, the questionnaire was designed based on the literature review and given to the experts to finalize it. Pilot testing was also conducted by the experts to finalize the factors. Once the factors were finalized the interview was organized for experts to fill in the response sheet and each interview took approximately 45 minutes for experts to give their views. The DEMATEL approach then scrutinized these barriers to determine their significance and establish the relationship between each of the factors and to examine the influencing factor of one on the other.

Research Methodology Approach

In the era of the digital world, using technology in teaching has always been beneficial in enhancing students' overall development. Adoption of AR in education has also given various benefits to children in enhancing their motivation, critical Thinking, improving subject concepts, and overall learning are all important aspects of child growth (Shankar et al., 2021; Wedel et al., 2020; Alalwan et al., 2020; Yılmaz et al., 2023). The major concern is its complete adoption in schools. Those barriers that affect the successful adoption of AR in the education sector were identified from a literature review and a questionnaire was designed and was verified by experts before being distributed for analysis. Experts were selected from all over India who are working in mobile applications or are an educationist and policy makers based on convenience sampling. The questionnaire was filled by 9 industry expert and 9 educationists of the same domain from all over India based on convenience sampling. Finally, analysis was done to find the relevance of barriers and interdependence between each barrier using cause and effect relationships. Each responder completed the questionnaire on a scale of 0–3, where 0 indicates no influence, 1 indicates low influence, 2 indicates medium influence, and 3 indicates high influence. The questionnaire asked participants to rate the relative importance of two items in the same category by filling out a pairwise comparison matrix. If factor A significantly affects the other factor, the individual has completed factor 3, and so on for the other factors.

The phases of the decision structure model for AR adoption in education are shown in Fig. 2. below.

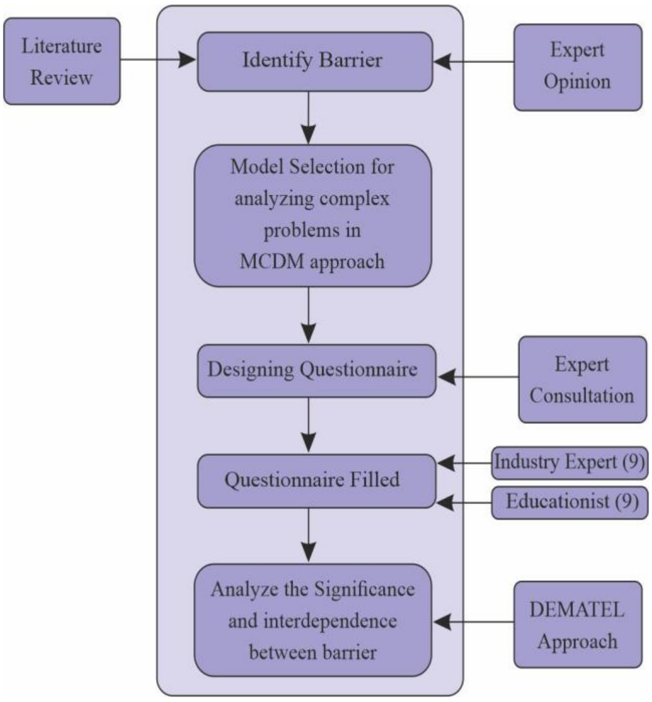

Fig. 2. Decision structure model for adoption of AR in education

DEMATEL Approach

The decision-making trial and evaluation laboratory (DEMATEL) method was developed in 1970 to solve complex problems (Aydoğdu, 2022; Fitria, 2022c; Yildiz, 2021; Nayak & D'Souza, 2019) in a multi-criteria decision-making process. Unlike the Analytical Hierarchical process (AHP), this method identifies the interdependence between elements using a cause-and-effect diagram (Aydoğdu, 2022; Fitria, 2022c; Yildiz, 2021). This method helps in understanding the cluster of problems and helps in identifying the workable solution by hierarchical structure (Shieh et al., 2010). Unlike the other MCDM techniques such as AHP which assume every factor as independent, this method, finds the interrelationship between each factor by using casual diagram. By leveraging this method, decision makers can better prioritize actions and allocate resources more efficiently in an interconnected challenge. This diagram represents direction lines to show the relative relationship and effect among the elements (Fitria, 2022c; Yildiz, 2021). DEMATEL also identify the most important factor to be taken care of based (c+r) value which identifies the degree of importance. The steps and process of the DEMATEL method are summarized below (Aydoğdu, 2022; Fitria, 2022c; Yildiz, 2021):

Step 1: To find the average matrix. Each responder was asked to rate the degree to which any two things directly influenced the other using scores ranging from 0, 1, 2, and 3 which meant ''no influence'', ''low influence'', ''medium influence'', and ''high influence'', respectively. The notation of a_{ij} shows the degree to which the responder believes factor i affects factor j. For i=j, the diagonal values are set to zero. For each respondent, an n*n non-negative matrix was established as $A^k = [a_{ij}^k]$, where k is the number of respondents with $1 \le k \le H$ and n is the number of factors. Thus, $A^1, A^2, A^3, \dots, A^H$ as are the matrices from H respondents. To incorporate all opinions from H respondents, the average matrix $B = [b_{ij}]$ was constructed as follows:

$$b_{ij} = \frac{1}{H}\sum_{K=1}^{H} a_{ij}^k \tag{1}$$

Step 2: Identify the initial direct-relation matrix and convert it into normalized form. First, normalize the matrix D by using $D = B \times S$, where $S = \frac{1}{\max_{1\le i\le n} \sum_{j=1}^{n} b_{ij}}$. In matrix D, each element ranges from zero to one.

Step 3: Then Calculate the total relation matrix. The total relation matrix T is defined as $T = D(I-D)^{-1}$, where I is the identity matrix. Define r and c to be n*1 and 1*n vectors showing the sum of rows and the sum of columns of the total relation matrix T, respectively. Suppose r_i is the sum of ith row in matrix T, then r_i summarizes both direct and indirect effects given by factor i to the other factors. If c_j indicates the sum of j^{th} column in matrix T, then c_j shows both direct and indirect effects by factor j from the other factors. When j=i, the sum $(r_i + c_j)$ shows the total effects given and received by factor i. That is, $(r_i + c_j)$ indicates the degree of importance that factor i plays in the entire system. On the contrary, the difference $(r_i - c_i)$ shows the net effect that factor *i* contribute to the system. If $(r_i - c_j)$ is positive, factor *i* is a net cause, while factor *i* is a net receiver or result if $(r_i - cj)$ is negative (Fernández-Batanero et al., 2022; Sırakaya & Alsancak Sırakaya, 2022).

Step 4: To get the digraph, set up a threshold value. A decision-maker must set up a threshold value to weed out certain insignificant impacts since matrix T shows how one element influences another. In doing so, only impacts that were bigger than the threshold value would be selected and displayed in the digraph. The threshold value in this study is determined by averaging the values in matrix T. One way to obtain the diagraph is to map the dataset of $(r + c, r - c)$.

Case for Adoption of AR in Education

In this case, a pair-wise matrix questionnaire was designed to take expert opinions from the industry and education sector. A questionnaire containing 6 barriers was sent to 18 experts from industry, Application development of AR/VR technology, institute heads, and other education leaders from all over India. Each respondent completed the questionnaire on a scale of 0–3, with 0 representing no influence and 1 indicates low influence, 2 indicates medium influence, and 3 indicates high influence. In the questionnaire participants have filled pair wise comparison matrix based on the importance of one factor on the other factor in the same category. If factor A has high impact on the other factor, then participant has filled 3 in that case and so on for the other factors. Demographic details of participants are given in Table 2. Major six barriers include (A) Adaptable to New Technology, (B) Availability of Funds, (C) Quality Content, (D) Layout and Design, (E) Effective Pedagogy, and (F) Technical Challenges.

Response of each respondent is shown in the matrices that are shown below:

$$A^1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 3 \\ 3 & 0 & 3 & 2 & 2 & 3 \\ 3 & 0 & 0 & 3 & 3 & 1 \\ 3 & 0 & 2 & 0 & 2 & 1 \\ 1 & 0 & 3 & 3 & 0 & 0 \\ 3 & 0 & 3 & 3 & 3 & 0 \end{bmatrix} \quad A^2 = \begin{bmatrix} 0 & 2 & 2 & 1 & 2 & 2 \\ 3 & 0 & 3 & 2 & 2 & 1 \\ 2 & 1 & 0 & 2 & 3 & 1 \\ 2 & 1 & 2 & 0 & 3 & 2 \\ 1 & 0 & 2 & 1 & 0 & 0 \\ 3 & 2 & 2 & 2 & 1 & 0 \end{bmatrix}$$

$$A^3 = \begin{bmatrix} 0 & 3 & 3 & 3 & 1 & 3 \\ 3 & 0 & 3 & 3 & 2 & 2 \\ 3 & 1 & 0 & 0 & 3 & 1 \\ 2 & 1 & 2 & 0 & 2 & 1 \\ 3 & 1 & 3 & 1 & 0 & 3 \\ 3 & 0 & 1 & 1 & 1 & 0 \end{bmatrix} \quad A^4 = \begin{bmatrix} 0 & 3 & 2 & 3 & 3 & 2 \\ 3 & 0 & 2 & 1 & 1 & 1 \\ 1 & 3 & 0 & 2 & 3 & 2 \\ 2 & 1 & 3 & 0 & 0 & 2 \\ 3 & 2 & 1 & 0 & 0 & 1 \\ 0 & 2 & 3 & 2 & 2 & 0 \end{bmatrix}$$

$$A^5 = \begin{bmatrix} 0 & 2 & 1 & 3 & 2 & 1 \\ 2 & 0 & 2 & 1 & 1 & 2 \\ 3 & 2 & 0 & 3 & 1 & 3 \\ 1 & 3 & 2 & 0 & 1 & 2 \\ 2 & 3 & 2 & 1 & 0 & 1 \\ 1 & 1 & 2 & 2 & 1 & 0 \end{bmatrix} \quad A^6 = \begin{bmatrix} 0 & 3 & 2 & 2 & 2 & 2 \\ 3 & 0 & 2 & 3 & 2 & 2 \\ 2 & 2 & 0 & 3 & 3 & 2 \\ 3 & 3 & 2 & 0 & 2 & 2 \\ 2 & 3 & 2 & 2 & 0 & 3 \\ 3 & 3 & 2 & 3 & 2 & 0 \end{bmatrix}$$

$$A^7 = \begin{bmatrix} 0 & 3 & 3 & 3 & 3 & 2 \\ 3 & 0 & 2 & 1 & 0 & 2 \\ 2 & 1 & 0 & 3 & 3 & 2 \\ 1 & 1 & 3 & 0 & 3 & 3 \\ 2 & 2 & 3 & 3 & 0 & 2 \\ 2 & 3 & 2 & 2 & 2 & 0 \end{bmatrix} \quad A^8 = \begin{bmatrix} 0 & 2 & 1 & 2 & 2 & 1 \\ 2 & 0 & 2 & 3 & 2 & 2 \\ 2 & 2 & 0 & 2 & 2 & 1 \\ 3 & 2 & 3 & 0 & 3 & 1 \\ 3 & 3 & 2 & 2 & 0 & 1 \\ 1 & 2 & 2 & 1 & 1 & 0 \end{bmatrix}$$

$$A^9 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 2 \\ 0 & 0 & 1 & 2 & 3 & 2 \\ 1 & 1 & 0 & 2 & 1 & 2 \\ 0 & 2 & 1 & 0 & 1 & 2 \\ 2 & 2 & 1 & 1 & 0 & 3 \\ 2 & 1 & 2 & 1 & 3 & 0 \end{bmatrix} \quad A^{10} = \begin{bmatrix} 0 & 1 & 0 & 1 & 3 & 3 \\ 0 & 0 & 3 & 2 & 1 & 3 \\ 0 & 1 & 0 & 1 & 0 & 3 \\ 0 & 2 & 0 & 0 & 1 & 3 \\ 2 & 3 & 2 & 1 & 0 & 3 \\ 3 & 2 & 1 & 3 & 2 & 0 \end{bmatrix}$$

$$A^{11} = \begin{bmatrix} 0 & 2 & 1 & 1 & 2 & 2 \\ 2 & 0 & 3 & 1 & 1 & 1 \\ 2 & 2 & 0 & 1 & 2 & 2 \\ 2 & 3 & 2 & 0 & 3 & 3 \\ 3 & 2 & 2 & 2 & 0 & 2 \\ 2 & 2 & 3 & 3 & 1 & 0 \end{bmatrix} \quad A^{12} = \begin{bmatrix} 0 & 1 & 2 & 2 & 3 & 2 \\ 1 & 0 & 2 & 2 & 2 & 3 \\ 1 & 2 & 0 & 2 & 2 & 2 \\ 1 & 1 & 1 & 0 & 1 & 1 \\ 3 & 2 & 2 & 2 & 0 & 2 \\ 2 & 1 & 1 & 1 & 1 & 0 \end{bmatrix}$$

$$A^{13} = \begin{bmatrix} 0 & 2 & 2 & 2 & 3 & 2 \\ 1 & 0 & 2 & 2 & 2 & 3 \\ 1 & 2 & 0 & 0 & 2 & 2 \\ 1 & 1 & 1 & 0 & 3 & 1 \\ 3 & 2 & 2 & 2 & 0 & 2 \\ 2 & 1 & 1 & 1 & 1 & 0 \end{bmatrix} \quad A^{14} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 2 \\ 0 & 0 & 1 & 2 & 2 & 2 \\ 1 & 1 & 0 & 2 & 1 & 2 \\ 0 & 2 & 1 & 0 & 1 & 2 \\ 2 & 2 & 1 & 1 & 0 & 3 \\ 2 & 1 & 2 & 1 & 3 & 0 \end{bmatrix}$$

$$A^{15} = \begin{bmatrix} 0 & 2 & 2 & 2 & 1 & 2 \\ 1 & 0 & 1 & 2 & 2 & 2 \\ 2 & 2 & 0 & 1 & 1 & 2 \\ 2 & 2 & 1 & 0 & 1 & 1 \\ 2 & 1 & 1 & 2 & 0 & 1 \\ 2 & 1 & 1 & 1 & 2 & 0 \end{bmatrix} \quad A^{16} = \begin{bmatrix} 0 & 3 & 3 & 3 & 1 & 3 \\ 3 & 0 & 3 & 3 & 2 & 2 \\ 3 & 1 & 0 & 0 & 3 & 1 \\ 2 & 1 & 2 & 0 & 2 & 1 \\ 3 & 1 & 3 & 1 & 0 & 3 \\ 3 & 0 & 1 & 1 & 1 & 0 \end{bmatrix}$$

$$A^{17} = \begin{bmatrix} 0 & 3 & 3 & 2 & 1 & 2 \\ 3 & 0 & 3 & 3 & 2 & 2 \\ 3 & 1 & 0 & 0 & 3 & 1 \\ 2 & 1 & 2 & 0 & 2 & 1 \\ 3 & 1 & 2 & 1 & 0 & 3 \\ 3 & 0 & 1 & 1 & 1 & 0 \end{bmatrix} \quad A^{18} = \begin{bmatrix} 0 & 3 & 2 & 2 & 2 & 2 \\ 3 & 0 & 2 & 3 & 2 & 2 \\ 2 & 2 & 0 & 3 & 3 & 2 \\ 3 & 3 & 2 & 0 & 2 & 2 \\ 2 & 3 & 2 & 2 & 0 & 3 \\ 3 & 3 & 2 & 3 & 2 & 0 \end{bmatrix}$$

Table 2: Demographic Details of Participants

Demographic	Characteristics	Frequency (N=18)	Percentage (%)
Gender	Male	13	72.22
	Female	5	27.78
Age	Below 30 years old	3	16.67
	31-40	9	50
	41-50	5	27.78
	51 and above	1	5.56
Profession	Policy Makers	5	27.78
	Mobile Application Developers	10	55.56
	Educational Heads	3	16.67
			27
Experience	0-10	3	16.67
	11-20	11	61.11
	21-30	2	11.11
	31-40	1	5.56
	>40	1	5.56

Step 1: The average matrix B was constructed in MS Excel from Equation (1) as follows:

$$B = \begin{bmatrix} 0.0 & 1.9 & 1.6 & 1.7 & 1.7 & 2.1 \\ 2.0 & 0.0 & 2.2 & 2.1 & 1.7 & 2.0 \\ 1.8 & 1.5 & 0.0 & 1.6 & 2.1 & 1.7 \\ 1.6 & 1.6 & 1.7 & 0.0 & 1.8 & 1.7 \\ 2.3 & 1.8 & 2.0 & 1.5 & 0.0 & 2.0 \\ 2.2 & 1.3 & 1.7 & 1.7 & 1.6 & 0.0 \end{bmatrix}$$

Step 2: To calculate the normalized initial direct-relation matrix D was calculated as below: -

$$\begin{bmatrix} 0.00000 & 0.19231 & 0.15934 & 0.17582 & 0.17033 & 0.20879 \\ 0.19780 & 0.00000 & 0.21978 & 0.20879 & 0.17033 & 0.20330 \\ 0.18681 & 0.14835 & 0.00000 & 0.16484 & 0.21429 & 0.17582 \\ 0.16484 & 0.16484 & 0.17582 & 0.00000 & 0.18132 & 0.17033 \\ 0.23077 & 0.18132 & 0.19780 & 0.15385 & 0.00000 & 0.19780 \\ 0.21978 & 0.13736 & 0.17582 & 0.17582 & 0.16484 & 0.00000 \end{bmatrix}$$

Step 3: The total relation matrix $T = D(I-D)^{-1}$ was calculated as shown below:

$$\begin{bmatrix} 1.722680 & 1.664711 & 1.793804 & 1.734350 & 1.765870 & 1.887795 \\ 2.085098 & 1.628979 & 1.975083 & 1.890162 & 1.902972 & 2.026563 \\ 1.903160 & 1.610345 & 1.629933 & 1.700247 & 1.773218 & 1.837573 \\ 1.831277 & 1.574975 & 1.728159 & 1.509935 & 1.698950 & 1.779693 \\ 2.052144 & 1.734500 & 1.905395 & 1.799084 & 1.703931 & 1.968178 \\ 1.901090 & 1.581596 & 1.755502 & 1.686864 & 1.715104 & 1.668340 \end{bmatrix}$$

Step 4: The threshold value 1.762015 is obtained by the average of matrix T. This value is used to filter out the negligible effects or eliminating the relationship with weak influence and hence helps in creating digraph with cause-and-effect relationship between barriers. Systematic DEMATEL approach is diagrammatically explained in Fig. 3. below:

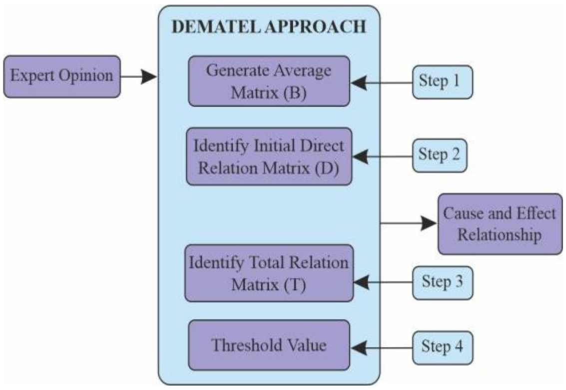

Fig. 3. Systematic DEMATEL Approach

Results and Discussion

This section presents the analytical results derived from the DEMATEL method, focusing on two key dimensions: the degree of importance (prominence) of each barrier and the causal relationships between them. Based on the average matrix (D) calculated from expert responses, the prominence $(c + r)$ and relation $(c - r)$values were computed to categorize the barriers into cause-and-effect groups.

The analysis reveals that Adaptability to New Technology (A) is the most critical factor within the system, exhibiting the highest prominence value $(c + r = 22.1646)$. This indicates that adaptability is the central issue that must be prioritized before implementing AR in schools. Furthermore, the causal analysis identifies Financial Constraints(B) and Effective Pedagogy (E) as the primary causal factors, meaning they influence the other barriers. Conversely, Adaptability (A), Quality Content (C), Technical Challenges (F), and Interface Design(D) are classified as effect factors, meaning they are largely influenced by the driving causes.

Degree of Importance

The degree of importance, represented by the $(\boldsymbol{c} + \boldsymbol{r})$ values in Table 3, indicates the overall prominence of each factor; a higher value signifies a greater influence within the structural model. As shown in Table 3, the barriers are ranked by importance in the following descending order:

$$\boldsymbol{A > E > F > B > C > D}$$

Consequently, Adaptability to New Technology (A) is identified as the most significant barrier, while Layout and Design (D) holds the lowest degree of prominence in the current context.

Table 3. Direct and Indirect Effects

Code	Barrier	$c + r$	$r - c$	Identity
A	Adaptability	22.1646	-0.926239	Effect
B	Financial Constraints	21.3037	1.7139316	Cause
C	Quality Content	21.2423	-0.3333995	Effect
D	Interface Design	20.4434	-0.1978327	Effect
E	Effective Pedagogy	20.4434	0.6031859	Cause
F	Technical Infrastructure	21.4766	-0.8596463	Effect

Cause and Effect Barriers

The structural relationships among the barriers were determined by plotting the factors on a cause-and-effect diagraph, as illustrated in Fig. 4. The horizontal axis represents the prominence value $(ci + ri)$, and the vertical axis represents the relation value $(ci - ri)$The dividing points for the axes were set using the mean value for the horizontal axis and 0.0 for the vertical axis.

The analysis of the relation values $(ci - ri)$ in Table 3 classifies the barriers into two groups:

1. **Causal Factors (Causes):** Factors with positive $(ci - ri)$ values are the primary driving forces within the system. These include Availability of Funds (B) and Effective Pedagogy (E). These causes require strategic emphasis, as they heavily influence the state of the other barriers.
2. **Effect Factors (Effects):** Factors with negative $(ci - ri)$values are influenced by the causal factors. These include Adaptability (A), Quality Content (C), Technical Challenges (F), and Layout and Design (D).

This categorization implies that for successful AR adoption, the education sector must primarily address the core causes (Funding and Pedagogy) to automatically mitigate the effects (such as poor Adaptability and Technical Challenges).

Creating the Cause-and-Effect Diagraph

To construct the directed causal graph (Fig. 4.), a threshold value was calculated from the average of the total relation matrix T. The derived threshold value is 1.762015. This value was used to filter out negligible effects, simplifying the visualization of the structural relationships.

Matrix L (shown below) was formed by comparing the values in the normalized initial direct relation matrix against this threshold. A value of 1 in Matrix L signifies a significant directional influence between two barriers, while 0 indicates a negligible or absent effect. This matrix is directly used to draw the directional lines in the cause-and-effect diagraph (Fig. 4.), providing a clear map of the dependencies for future researchers to determine the most impactful intervention points.

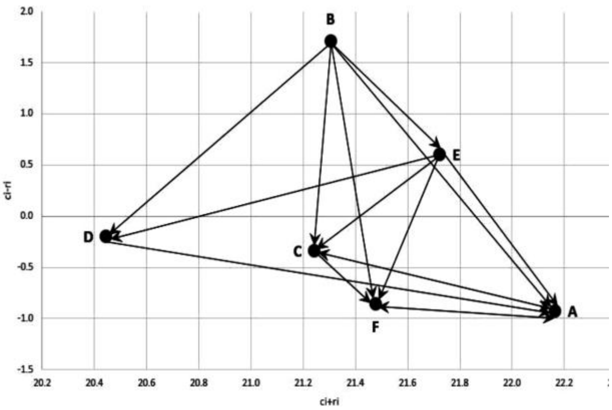

Fig. 4. Cause and Effect Relationship

Conclusion

This study concludes by analyzing the major barriers to the adoption of Augmented Reality (AR) in the education sector, utilizing the Decision-Making Trial and Evaluation Laboratory (DEMATEL) approach to uncover the complex interdependence between these factors.

We found that the main factors influencing successful AR adoption are the Availability of Funds (B), Effective Pedagogy (E), Adaptability (A), Quality Content (C), Layout and Design (D), and Technical Challenges (F). A significant finding is the classification of Funds (B) and Pedagogy (E) as the primary causal factors driving the system's structure.

This research demonstrates that by focusing on these core causes, educational stakeholders can ensure the necessary funds and pedagogical approaches are in place to automatically mitigate the effect factors, such as poor adaptability and technical challenges. Implementing a proper pedagogical approach, coupled with funding initiatives from the government and institutes, increases the likelihood of widespread adoption. This research provides actionable insights to assist industry professionals, institute heads, and educators in creating more effective AR applications in the real world.

Future Scope

The potential for developers, learners, and educators in the future of AR applications is immense. To increase the successful adoption of these technologies, future research can build upon the current findings in several key areas:

Diverse Expert Analysis: Data collection and analysis from a more diverse group of experts, including developers, teachers, and policymakers, can further validate and refine the identified barriers.

Contextual Comparison: Researchers could employ statistical methods to investigate the barriers across different age groups, subject areas, and geographical locations to provide better comparative insights for integrating AR technology into the education sector.

Impact of Integrated Systems: Future studies should examine the impact of integrating Artificial Intelligence (AI) with AR applications on learning outcomes, specifically how addressing these identified barriers influences the overall effectiveness of the combined system.

Long-Term Behavioral Study: Further research is needed to investigate the long-term impact and behavioral patterns of augmented reality use on students, focusing on improving motivation, conceptual understanding, critical thinking, and engagement.

This targeted research will provide policymakers and educators with the insights needed to identify the best approaches for improving educational standards and enhancing student learning outcomes.

Ethics

This article does not contain any studies with human participants or animals performed by any of the authors.

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Funding Information

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author Contributions

Monika Nijhawan: Conceptualization; Data Curation; Formal Analysis; Writing - Original Draft.

Nidhi Sindhwani: Supervision; Writing - Review & Editing; Resources.

Sarvesh Tanwar: Methodology; Validation; Writing - Review & Editing.

Shishir Kumar: Investigation; Resources; Writing - Review & Editing.

References

Akçayır, M., & Akçayır, G. (2017). Advantages and challenges associated with augmented reality for education: A systematic review of the literature. *Educational Research Review, 20*, 1–11.

Alalwan, N., Cheng, L., Al-Samarraie, H., Yousef, R., Alzahrani, A. I., & Sarsam, S. M. (2020). Challenges and prospects of virtual reality and augmented reality utilization among primary school teachers: A developing country perspective. *Studies in Educational Evaluation, 66*, 100876.

AR, G. A. (2024). Augmented reality in retail: Metrics in the furniture department. *IAENG International Journal of Computer Science, 51*(8).

Aydoğdu, F. (2022). Augmented reality for preschool children: An experience with educational contents. *British Journal of Educational Technology, 53*(2), 326–348.

Behl, A., Dutta, P., & Gupta, S. (2019). Critical success factors for humanitarian supply chain management: A grey DEMATEL approach. *IFAC-PapersOnLine, 52*(13), 159–164.

Bistaman, I. N. M., Idrus, S. Z. S., & Abd Rashid, S. (2018). The use of augmented reality technology for primary school education in Perlis, Malaysia. *Journal of Physics: Conference Series, 1019*(1), 012064.

Børte, K., Nesje, K., & Lillejord, S. (2023). Barriers to student active learning in higher education. *Teaching in Higher Education, 28*(3), 597–615.

Criollo-C, S., Guerrero-Arias, A., Guaña-Moya, J., Samala, A. D., & Luján-Mora, S. (2024). Towards sustainable education with the use of mobile augmented reality in early childhood and primary education: A systematic mapping. *Sustainability, 16*(3), 1192.

Fan, M., Antle, A. N., & Warren, J. L. (2020). Augmented reality for early language learning: A systematic review of augmented reality application design, instructional strategies, and evaluation outcomes. *Journal of Educational Computing Research, 58*(6), 1059–1100.

Fernández-Batanero, J. M., Montenegro-Rueda, M., & Fernández-Cerero, J. (2022). Use of augmented reality for students with educational needs: A systematic review (2016–2021). *Societies, 12*(2), 36.

Fitria, T. N. (2022). Using game design techniques (gamification) in teaching and learning process: A review. *Presiding Seminar Nasional & Call for Paper STIE AAS, 5*(1), 1–18.

Fitria, T. N. (2023). Augmented reality (AR) and virtual reality (VR) technology in education: Media of teaching and learning: A review. *International Journal of Computer and Information System, 4*(1), 14–25.

Garzón, J., Baldiris, S., Gutiérrez, J., & Pavón, J. (2020). How do pedagogical approaches affect the impact of augmented reality on education? A meta-analysis and research synthesis. *Educational Research Review, 31*, 100334.

Hamutoglu, N. B., & Basarmak, U. (2020). External and internal barriers in technology integration: A structural regression analysis. *Journal of Information Technology Education: Research, 19*.

Iqbal, M. Z., Mangina, E., & Campbell, A. G. (2022). Current challenges and future research directions in augmented reality for education. *Multimodal Technologies and Interaction, 6*(9), 75.

John, B., Kurian, J. C., Fitzgerald, R., & Goh, D. H. L. (2022). Students' learning experience in a mixed reality environment: Drivers and barriers. *Communications of the Association for Information Systems, 50*(1), 510–535.

Kazancoglu, Y., & Ozkan-Ozen, Y. D. (2018). Analyzing Workforce 4.0 in the Fourth Industrial Revolution and proposing a road map from operations management perspective with fuzzy DEMATEL. *Journal of Enterprise Information Management, 31*(6), 891–907.

Laferrière, T., Hamel, C., & Searson, M. (2013). Barriers to successful implementation of technology integration in educational settings: A case study. *Journal of Computer Assisted Learning, 29*(5), 463–473.

Lai, J. W., & Cheong, K. H. (2022). Educational opportunities and challenges in augmented reality: Featuring implementations in physics education. *IEEE Access, 10*, 43143–43158.

Lampropoulos, G., Keramopoulos, E., Diamantaras, K., & Evangelidis, G. (2022). Augmented reality and gamification in education: A systematic literature review of research, applications, and empirical studies. *Applied Sciences, 12*(13), 6809.

Lee, K. (2012). Augmented reality in education and training. *TechTrends, 56*(2), 13–21.

Lee, Y. C., Yen, T. M., & Tsai, C. H. (2008). Using importance-performance analysis and decision-making trial and evaluation laboratory to enhance order-winner criteria: A study of computer industry. *Information Technology Journal, 7*(3), 396–408.

López-Faican, L., & Jaen, J. (2020). EmoFindAR: Evaluation of a mobile multiplayer augmented reality game for primary school children. *Computers & Education, 149*, 103814.

Martínez-Torres, M. D. R., Toral Marín, S. L., García, F. B., Vázquez, S. G., Oliva, M. A., & Torres, T. (2008). A technological acceptance of e-learning tools used in practical and laboratory teaching, according to the European higher education area. *Behaviour & Information Technology, 27*(6), 495–505.

Matsika, C., & Zhou, M. (2021). Factors affecting the adoption and use of AVR technology in higher and tertiary education. *Technology in Society, 67*, 101694.

Mohammed, B. (2024). The synergy of explainable AI and learning analytics in shaping educational insights. *IAENG International Journal of Computer Science, 51*(9).

Nayak, V., & D'Souza, R. G. (2019). Comparison of multi-criteria decision-making methods used in requirement engineering. *CiiT International Journal of Artificial Intelligent Systems and Machine Learning, 11*(5), 92–96.

Nincarean, D., Alia, M. B., Halim, N. D. A., & Rahman, M. H. A. (2013). Mobile augmented reality: The potential for education. *Procedia – Social and Behavioral Sciences, 103*, 657–664.

Oke, A. E., & Arowoiya, V. A. (2022). Critical barriers to augmented reality technology adoption in developing countries: A case study of Nigeria. *Journal of Engineering, Design and Technology, 20*(5), 1320–1333.

Okoye, K., Hussein, H., Arrona-Palacios, A., Quintero, H. N., Ortega, L. O. P., Sanchez, A. L., & Hosseini, S. (2023). Impact of digital technologies upon teaching and learning in higher education in Latin America: An outlook on the reach, barriers, and bottlenecks. *Education and Information Technologies, 28*(2), 2291–2360.

Pellas, N., Fotaris, P., Kazanidis, I., & Wells, D. (2019). Augmenting the learning experience in primary and secondary school education: A systematic review of recent trends in augmented reality game-based learning. *Virtual Reality, 23*(4), 329–346.

Perifanou, M., Economides, A. A., & Nikou, S. A. (2022). Teachers' views on integrating augmented reality in education: Needs, opportunities, challenges and recommendations. *Future Internet, 15*(1), 20.

Shankar, V., Kalyanam, K., Setia, P., Golmohammadi, A., Tirunillai, S., Douglass, T., & Waddoups, R. (2021). How technology is changing retail. *Journal of Retailing, 97*(1), 13–27.

Shieh, J. I., Wu, H. H., & Huang, K. K. (2010). A DEMATEL method in identifying key success factors of hospital service quality. *Knowledge-Based Systems, 23*(3), 277–282.

Sırakaya, M., & Alsancak Sırakaya, D. (2022). Augmented reality in STEM education: A systematic review. *Interactive Learning Environments, 30*(8), 1556–1569.

Sitopu, J. W., Khairani, M., Roza, M., Judijanto, L., & Aslan, A. (2024). The importance of integrating mathematical literacy in the primary education curriculum: A literature review. *International Journal of Teaching and Learning, 2*(1), 121–134.

Sumrit, D., & Anuntavoranich, P. (2013). Using DEMATEL method to analyze the causal relations on technological innovation capability evaluation factors in Thai technology-based firms. *International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies, 4*(2), 81–103.

Tseng, J. L. (2020). Raising the learning effects for learners with low entrance scores using project-based learning in virtual reality practice. *IAENG International Journal of Computer Science, 47*(3), 516–521.

Tuli, N., & Mantri, A. (2021). Evaluating usability of mobile-based augmented reality learning environments for early childhood. *International Journal of Human–Computer Interaction, 37*(9), 815–827.

Tzeng, G. H., Chiang, C. H., & Li, C. W. (2007). Evaluating intertwined effects in e-learning programs: A novel hybrid MCDM model based on factor analysis and DEMATEL. *Expert Systems with Applications, 32*(4), 1028–1044.

Van Krevelen, D. W. F., & Poelman, R. (2010). A survey of augmented reality technologies, applications and limitations. *International Journal of Virtual Reality, 9*(2), 1–20.

Wedel, M., Bigné, E., & Zhang, J. (2020). Virtual and augmented reality: Advancing research in consumer marketing. *International Journal of Research in Marketing, 37*(3), 443–465.

Wu, H. K., Lee, S. W. Y., Chang, H. Y., & Liang, J. C. (2013). Current status, opportunities and challenges of augmented reality in education. *Computers & Education, 62*, 41–49.

Wu, W. W. (2008). Choosing knowledge management strategies by using a combined ANP and DEMATEL approach. *Expert Systems with Applications, 35*(3), 828–835.

Yang, W. T., Liu, W. H., & Liu, H. H. (2013). Evaluating influential factors in event quality using DEMATEL method. *International Journal of Trade, Economics and Finance, 4*(3), 92.

Yavuz, M., Çorbacıoğlu, E., Başoğlu, A. N., Daim, T. U., & Shaygan, A. (2021). Augmented reality technology adoption: Case of a mobile application in Turkey. *Technology in Society, 66*, 101598.

Yildiz, E. P. (2021). Augmented reality research and applications in education. *Augmented Reality and Its Application, 3*.

Yilmaz, Z. A., & Gözüm, A. İ. C. (2023). Augmented reality app in pre-school education: Children's knowledge about animals. *Southeast Asia Early Childhood, 12*(2), 130–151.

Zander, V., Gustafsson, C., Landerdahl Stridsberg, S., & Borg, J. (2023). Implementation of welfare technology: A systematic review of barriers and facilitators. *Disability and Rehabilitation: Assistive Technology, 18*(6), 913–928.