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Edtech on the rise: the role of robots in education and its economic implications

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Abstract: The purpose of this study is to synthesize the benefits and challenges of the use of educational robots across different countries and to examine their impact towards the economics of education. This study employed a qualitative analysis approach with the use of data mining methods. The data mining methods focused on gathering insights from existing academic journals and scholarly articles. This approach aim to understand the underlying themes and contexts within the data set by applying techniques such as content analysis, grounded theory, and thematic analysis. Results revealed that common educational robots used across countries are the assistive robots, humanoid robots, and modular robots. These robots serve various functions, from enhancing students learning experiences to assisting in both instructional and administrative tasks. However, widespread integration of educational robots present challenges such as high cost and training requirements, technical inhibitors, and concerns on cultural and contextual adaptability. Considerable investments would help ensure that the benefits of educational robots outweigh the financial challenges associated with such technologies.

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INTRODUCTION

The rapid evolution of technology is sparking a revolution in the field of education. Among these innovations, educational robots are emerging as key enablers of transformation, reshaping how students interact with content, how teachers deliver instruction, and how education systems are structured (Haidegger et al., 2023). These robots, with their ability to engage students in interactive and hands-on learning, are not only enhancing educational outcomes but also prompting a rethinking of pedagogical strategies and the broader economics of education. When viewed through the lens of Human Capital Theory, which emphasizes the importance of investing in skills and knowledge to drive economic growth, the integration of robots in education becomes a strategic move to enhance human capital by equipping students with critical, future-oriented skills (Ajani et al., 2024).

This shift toward Education 5.0—an era of personalized, technology-driven learning experiences—is being facilitated by a range of educational robots, from humanoid assistants to interactive learning tools (Asaad et al., 2024). These robots are deployed to support diverse student needs, offering tailored assistance, real-time feedback, and immersive learning opportunities (Hernandez-de-Menendez et al., 2020). They are especially valuable in promoting engagement, advancing STEM education, and extending support to underserved or resource-limited environments (Gan et al., 2024). By aligning educational practices with the demands of a technology-centric labor market, robots help cultivate the skills necessary for future workforce participation, as emphasized in Human Capital Theory (Calì & Presidente, 2022).

However, the integration of robotics in education presents significant challenges. While these advancements offer the potential for substantial improvements in learning effectiveness, they also raise important economic questions. The high costs of implementing and maintaining robotic systems, the risk of displacing traditional educational jobs, and the unequal access to these technologies are critical issues that must be addressed (Boyd & Holton, 2018; West, 2015). The economic implications of widespread robotic adoption extend beyond just financial costs, touching on equity, sustainability, and the long-term impact on both educational outcomes and resource allocation (Gomes & Pereira, 2020; Višić, 2020).

Statement of the problem

This research seeks to explore the dual dimensions of educational robotics: its transformative role in educational practices and its broader economic implications. By examining how robots influence student engagement, learning outcomes, and teaching strategies, alongside analyzing the challenges that emerge from their integration, this study aims to provide insights into the future of education in an increasingly automated world.

METHODOLOGY

Research design

This study employed a data mining approach to analyze the role of robots in education, evaluate the challenges associated with their use, and explore the economic implications of integrating robots into educational systems. The research involved collecting data from academic journals, case studies, policy reports, and educational databases, focusing on the impact of robots on teaching, learning, and economic considerations like implementation and maintenance costs.

Locale of the study and respondents

The study covered global educational contexts, including both developed and developing countries. Data was gathered from educational institutions at various levels (primary, secondary, and higher education) and relevant policy documents and academic publications. The respondents primarily consisted of the data sources themselves, such as case studies, academic articles, and policy reports, which reflected the perspectives of educators, administrators, and researchers on the integration of robots in education.

Data analyses procedure

Data was analyzed through clustering, association rule mining, and sentiment analysis to uncover patterns and relationships related to the use of robots in education. Clustering techniques grouped similar data points, while association rule mining identified key factors contributing to the successful integration of robots. Sentiment analysis was used to assess stakeholders' perceptions of robots in educational contexts. The results were cross-referenced with existing literature to verify their validity and reliability, ensuring a comprehensive understanding of the opportunities and challenges associated with robotics in education.

FINDINGS AND DISCUSSION

This section outlines the variables analyzed, focusing on the integration of robots into educational systems, specifically examining their role in enhancing teaching and learning, the challenges associated with their use, and their economic implications. The analysis addresses the impact of robots on student engagement, academic performance, and pedagogical strategies, while also evaluating the technological, pedagogical, and financial barriers to their adoption. By exploring these dimensions, the study aims to provide insights into how educational robots can transform learning experiences and inform policy decisions related to their integration in diverse educational contexts.

Types of educational robots and their functions

The most commonly used types of robots in educational settings across various countries include modular robots, humanoid robots, and assistive robots, each of which serves distinct educational purposes.

Modular robots

Modular robots are robotic systems composed of multiple, physically independent modules that can autonomously or semi-autonomously connect and disconnect to reconfigure their structure, with flexible interconnection mechanisms that allow adaptation to various tasks and environments, providing increased versatility, scalability, and fault tolerance, particularly useful in dynamic or unpredictable conditions where traditional, rigid robots may be limited (Chen & Yim, 2016).

Modular robots are playing a pivotal role in advancing STEM education and improving educational outcomes across countries. In Singapore, for instance, modular robots help students develop critical 21st-century skills like problem-solving, creativity, and technological literacy (PlayFACTO School, 2023). This approach aligns with the country's broader economic goals of preparing students for a technology-driven workforce. Similarly, in Canada, the use of Bee-Bots in underserved communities addresses educational equity by enhancing STEM learning and improving problem-solving skills, helping to close gaps in access to quality education (Dorsey & Howard, 2011). By making STEM subjects more engaging and accessible, these robots are investing in human capital, a key factor for long-term economic productivity and social mobility.

The use of modular robots in countries like Greece and Chile also highlights their potential to foster technological innovation and critical thinking. In Greece, modular robots promote technological literacy, while in Chile, they motivate students, particularly those who are disengaged from traditional teaching methods, to explore STEM fields (Alimisis, 2013; Ruiz-del-Solar & Avilés, 2014). These educational technologies not only cultivate problem-solving skills but also contribute to the development of a future-ready workforce. By equipping students with the technical knowledge and innovation-driven mindset required by today's global economy, countries are investing in their ability to compete on the world stage, thus driving economic growth.

Furthermore, the integration of modular robots in education in countries like Tanzania and Peru underscores their role in preparing students for future technological challenges and fostering critical thinking (Lund, 2014; Karim et al., 2015). Modular robots are not just tools for teaching; they are investments in economic resilience, ensuring that students gain skills that will be essential in the rapidly evolving digital economy. By enhancing engagement with complex concepts and making learning more interactive, these robots provide a pathway for students in underserved areas to enter high-demand industries. This democratization of education contributes to reducing disparities, ultimately supporting the broader goals of inclusive growth and economic development.

Humanoid robots

Humanoid robots are robots designed to mimic the human body's physical structure and movement capabilities, typically featuring a head, torso, arms, and legs, with the goal of performing tasks in human-centric environments and interacting with humans in a natural, anthropomorphic manner (Stasse & Flayols, 2019).

The integration of humanoid robots in educational systems, as seen in countries like the Netherlands and the USA, represents a strategic investment in both quality education and economic sustainability. In the Netherlands, humanoid robots are used to enhance student engagement and language interaction, which improves educational outcomes and attracts more students (Goudzwaard et al., 2019). This adoption not only enhances the learning experience but also contributes to the financial sustainability of educational institutions by offering a unique selling point in an increasingly competitive global education market. Similarly, in the USA, humanoid robots are deployed as teaching assistants, providing personalized learning experiences and making complex concepts more accessible (Newton & Newton, 2019). This technological integration aligns with the educational system's goal of preparing students for a future driven by digital innovation, thus contributing to human capital development, a key driver of economic growth.

From an economic perspective, humanoid robots also promote efficiency and scalability in education. In Sweden, robots are used as interactive companions to personalize learning, improving student satisfaction and learning outcomes (Reich-Stiebert, 2015). This level of personalization allows for more effective use of educational resources, enabling teachers to focus on higher-level cognitive tasks while robots handle repetitive instructional roles. In countries like Mexico and New Zealand, humanoid robots are helping to develop critical thinking and problem-solving skills, preparing students for advanced technological careers (Ramírez-Montoya et al., 2023; Maclaurin et al., 2019). The economic benefits of such investments are clear: by preparing students for future industries, countries are ensuring a competitive and innovative workforce capable of driving technological and economic growth. This is particularly important in STEM fields, where the demand for skilled workers is rapidly growing. Therefore, the integration of humanoid robots in education not only enhances the learning environment but also helps meet the economic demand for advanced technical skills in an increasingly digital economy.

Assistive robots

Socially assistive robots are defined as robots designed to provide non-physical support to individuals, particularly in educational settings, by engaging with users in ways that promote learning, social interaction, and emotional well-being, often aiding students with special educational needs (Papadopoulos et al., 2020).

The use of social assistive robots in educational settings, as seen in Israel, Brazil, and Nigeria, highlights their potential to enhance educational accessibility and equity, particularly for students with diverse learning needs. In Israel, robots are employed to help children develop cognitive and social skills, including language proficiency, through interactive lessons and physical activities (Benzion, 2020). This approach not only makes learning more dynamic but also contributes to a more inclusive educational environment, where students of varying abilities can access personalized learning. From an economic perspective, such investments in assistive technology promote human capital development by ensuring that all students, regardless of their abilities, have the opportunity to succeed in education and enter the workforce with the necessary skills. This is crucial for building a knowledge economy where the full potential of every individual is harnessed.

Similarly, in Brazil, assistive robotics has been shown to significantly benefit children with learning disabilities by offering interactive and engaging learning experiences that improve both cognitive and motor skills (Da Guia Torres da Silva et al., 2022). This technology helps bridge educational gaps, ensuring that children with disabilities are not left behind in the educational system. By fostering inclusive education, assistive robots contribute to the economic development of the country by enabling all students to participate in and contribute to the workforce, thus enhancing social mobility and reducing disparities. In Nigeria, the integration of assistive robots further emphasizes educational equity, as they cater to the diverse needs of students with disabilities, ensuring a more engaging and accessible learning experience (Essien & Ntui, 2024). This focus on inclusion not only has long-term benefits for individual students but also contributes to national economic growth by creating a more skilled, diverse, and capable workforce. Therefore, investing in assistive robots aligns with broader economic goals of fostering an inclusive and productive society.

Challenges on the use of educational robots

Despite the potential benefits of the use of educational robots, common challenges were identified across countries. These challenges include issues such as cultural and contextual adaptability, technical inhibitors, and high costs and training requirements.

Concerns on cultural and contextual adaptability

Moniz and Krings (2016) highlight two key concerns in the use of educational robots: cultural and contextual adaptability, which requires robots to be sensitive to diverse social norms and values for positive interactions across various environments, and curriculum adaptability, emphasizing the need for robots to be designed to fit different educational contexts and curricula in order to effectively support diverse teaching and learning needs.

The challenges related to cultural and contextual adaptability of educational robots across countries are significant, as seen in Israel and Singapore. In Israel, the design and deployment of social assistive robots (SARs) prioritize their adaptability to diverse educational contexts, while also addressing ethical concerns such as privacy and the potential reduction in human interaction (Liberman-Pincu et al., 2024). This highlights the balance that must be struck between technological innovation and cultural sensitivity, as robots need to be tailored to the specific needs and values of different educational environments. Similarly, in Singapore, integrating robots into the existing curriculum requires substantial investments in teacher training and adjustments to teaching methods, making the process both time-consuming and resource-intensive (Chen & Yim, 2016). From an economic perspective, these challenges point to the need for significant upfront investment in teacher professional development and infrastructure, which could strain resources, particularly in schools with limited funding. The costs associated with such adaptations can slow down the widespread adoption of robotics, hindering their potential to improve educational outcomes and contribute to long-term economic development.

In other countries like the USA and Tanzania, cultural and contextual challenges also arise from concerns about the loss of human interaction and the lack of alignment with local curricula. In the USA, humanoid robots are met with skepticism due to fears that they might undermine social and emotional development, which are crucial components of a well-rounded education (Newton & Newton, 2019). These concerns relate directly to the economics of education, as investing in robots that could potentially replace human teachers in certain aspects might not yield the expected returns if the social and emotional development of students is compromised. Similarly, in Tanzania, modular robots face difficulties in aligning with the local curriculum, requiring additional investments in infrastructure and teacher preparation to ensure the technology is effectively integrated (Lund, 2014). These challenges emphasize that the economic feasibility of educational robotics is not solely dependent on the initial cost of the technology, but also on the contextual fit and the long-term investment required for successful implementation across diverse educational settings. Therefore, addressing these cultural and contextual challenges is essential for maximizing the economic and educational benefits of robotics in schools.

Technical inhibitors

Educational robotics faces several technical challenges that can impede its effective adoption in schools, including hardware limitations, the complexity of programming, and difficulties in integrating robots into existing educational infrastructures (Anwar et al., 2019).

The technical inhibitors to the integration of educational robots, as highlighted in countries like Israel, Greece, and Tanzania, reflect the significant barriers related to infrastructure and maintenance. In Israel, the integration of social assistive robots (SARs) into the education system requires not only reliable infrastructure but also ongoing technical support to ensure their smooth operation (Liberman-Pincu et al., 2024). This underscores the economic challenge of maintaining high-quality educational tools, as technical support and infrastructure investments are costly but necessary to sustain the use of advanced technology in classrooms. Similarly, in Greece, many schools lack the basic technological infrastructure such as computer labs and internet access, which makes it difficult to effectively use educational robots (Chatzopoulos et al., 2020). This highlights a significant issue in the economics of education, where the digital divideimpacts the equitable distribution of educational technology. Countries with weaker technological infrastructure must make substantial investments in upgrading facilities and ensuring consistent access to the internet and power, which can be prohibitively expensive, especially in economically disadvantaged areas.

In Mexico and Brazil, the challenges of integrating educational robots are also tied to the technological limitations of existing systems. In Mexico, many educational institutions cannot accommodate the advanced features of robots due to outdated infrastructure (Lopez-Caudana et al., 2020). This results in suboptimal use of the robots' potential, which impacts the return on investment for educational institutions. Similarly, in Brazil, the integration of assistive robots for visually impaired students requires substantial technological infrastructure, which many schools lack (Gonçalves et al., 2020). This further reinforces the economic strain faced by educational institutions in lower-income countries that are attempting to modernize their systems without the necessary financial resources. In Tanzania and Nigeria, issues such as erratic electricity and unreliable internet access exacerbate the technical challenges, limiting the effectiveness of educational robots in those regions (Lund, 2014; Abualrejal et al., 2022). These challenges not only hinder the educational benefits of robotics but also point to the larger economic implications of underfunded education systems in developing nations. As a result, governments and institutions must consider the cost-effectiveness of such investments and balance them with the necessary infrastructure improvements to ensure that the adoption of educational robots leads to meaningful and sustainable educational outcomes.

High cost and training requirements

The high initial and maintenance cost, and the need for specialized training for educators present significant barrier in the widespread adoption of the use of educational robots (Cheng et al., 2019) particularly in countries like Brazil, Greece, Mexico, Philippines, Singapore, and

USA. In Singapore, the complexity of designing and reconfiguring modular robots, coupled with their high price, limits their broad adoption in schools, as it requires substantial financial investment and specialized expertise (Chen & Yim, 2016). The high cost of robotics in Philippines further exacerbates the situation, where inadequate funding, limited access to technology, and a lack of specialized teacher training hinder the effective integration of robotics into public schools (Bantigue & Baraquia, 2023). From an economic perspective, these financial barriers create inequalities in educational access, as wealthier schools with more resources can afford to integrate robotics into their curricula, while schools in lower-income regions face substantial challenges. The disparity in access can contribute to a widening education gap, undermining efforts to build a knowledge-based economy where equal access to technology is crucial for developing future-ready skills.

Similarly, countries like the USA, Mexico, and Brazil face significant barriers due to high robotics costs and insufficient teacher training. In the USA, the high cost of advanced robots can lead to disparities between well-funded and underfunded schools, exacerbating educational inequities (Newton & Newton, 2019). The same challenge exists in Mexico, where the high costs of robots like NAO, coupled with the lack of trained personnel, restrict their adoption to wealthier schools (Lopez-Caudana et al., 2020). In Brazil, the need for specialized teacher training to effectively use educational robots adds another layer of complexity, with many educators lacking the necessary skills to integrate robotics into inclusive settings (Gonçalves et al., 2020). These challenges underline the economic strain faced by schools in low-income regions, where the cost of robotics technologies and the lack of skilled teachers hinder efforts to create more inclusive and effective learning environments. Addressing these issues requires a comprehensive approach involving not only financial investment in technology but also the creation of sustainable training programs for educators and targeted initiatives to make robotics more affordable and accessible to all schools, regardless of their funding.

CONCLUSIONS

Educational robots are being utilized across countries to enhance students learning experiences, and assist in both instructional and administrative tasks. These robots offer support to students and engage learners through interactive, hands-on experiences. However, challenges such as high costs of development and implementation, and the need for continuous technical support and training limit their usage. The economics of education are impacted with these challenges, schools and institutions need to weigh the potential benefits of educational robots against the financial stability of such technologies. While robots are proven to increase efficiency and accessibility, widespread adaptation may exacerbate inequalities most especially in less developed areas. Hence, investments must be made to ensure equitable access to these advanced learning tools across different educational systems and regions.

The integration of robots into education aligns with Human Capital Theory, which purports that investing in skills and knowledge lead to the increase of productivity and economic value. They can be seen as substantial investment in developing highly skilled workforce, since robots help cultivate critical thinking, problem-solving, and technical skills among learners. In a long run, the benefits of such educational robots in enhancing student learning could outweigh their costs, leading to greater human capital development and increased productivity in the labor market. However, careful consideration must be given to ensure equitable access, making sure that the advantages of these technologies do not exacerbate existing social and economic disparities.

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