Universidad
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DOCTORAL THESIS

Technological Acceptance of Augmented Reality in Engineering Education in Higher Education

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Abstract

The present doctoral thesis proposes a model for the acceptance of augmented reality technology to determine variables that influence its acceptance in the context of learning electrical circuits for engineering students.

First, a systematic review was conducted to determine the state-of-the-art use of augmented reality technology in engineering education. The results of this study shed light on the use of augmented reality in engineering education. They also allowed decisions to be made in the following stages of the proposed research, considering various aspects, from its educational use and evaluations to which it has been subjected to technical elements specific to this technology.

An augmented reality application was also developed for students to analyze resistive circuits. With a high level of interactivity, this application allowed students to simulate the behavior of series and parallel circuits, obtaining complex real-time responses, such as calculating voltages and currents flowing through each element incorporated into the circuit.

Finally, two theoretical models were conceived to explain the acceptance of augmented reality technology, relating *attitude towards using* and *behavioral intention to use* with the variables of *subjective norm*, *technology optimism*, and *technology innovativeness* in the first model, adding the variables of *perceived ease of use* and *perceived usefulness* in the second model.

Both models demonstrate the positive effect of *technology optimism* and *technology innovativeness* on *perceived usefulness* and *attitude towards using,* respectively. The above suggests that higher education institutions could raise awareness about the benefits of technological tools in learning to create technologically friendly environments and promote using these technologies. Additionally, they suggest that *attitude towards using* is influenced by *perceived usefulness* rather than directly by *perceived ease of use*. The above could mean that students would be willing to use this application if they find it useful and not just easy to use. Hence, it is important to disseminate the benefits obtained in academic performance when using this type of application.

The results demonstrate that *attitude towards using* firmly explains the *behavioral intention to use*, consistent with previous studies. These findings could guide how academics and higher education institutions incorporate these technologies into the classroom.

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Acronyms

ACM	Association for Computing Machinery
AR	Augmented Reality
ART	AR Technology Acceptance Framework
DC	Direct Current
HE-TAM	Haptic Enabling Technology Acceptance Model
IAR	Industrial Augmented Reality
IDT	Innovation and Diffusion Theory
IEEE	Institute of Electrical and Electronics Engineers
MOOC	Massive Online Open Courses
PLS	Partial Least Squares
QR	Quick Response Code
SDK	Software Development Kit
STEM	Science, Technology, Engineering y Mathematics
TAM	Technology Acceptance Model
TR	Technology Readiness
TRA	Theory of Reasoned Action
TRAM	Technology Readiness and Acceptance Model
UTAUT	Unified Theory of Acceptance and Use of Technology
VAM	Value-based Adoption Model
VR	Virtual Reality

List of Publications

This thesis, by compilation, is based on the work and results presented in the following five scientific articles, referenced in the text as P.I – P.V:

P.I Álvarez-Marín, A., and Velázquez-Iturbide, J.Á. (2021). Augmented reality and engineering education: A systematic review. In IEEE Transactions on Learning Technologies, 14(6), 817-831. doi: 10.1109/TLT.2022.3144356. JCR 2021: 4,43 - Education & Educational Research (Q1); SJR 2021: 1,29 - Computer Science Applications (Q1).

P.II Álvarez-Marín, A., Velázquez-Iturbide, J.Á., and Campos-Villarroel, R. (2021). Interactive AR app for real-time analysis of resistive circuits in interactive learning environments. In IEEE Revista Iberoamericana de Tecnologías del Aprendizaje, 16(2), 187-193. doi: 10.1109/RITA.2021.3089917. SJR 2021: 0,48 - Education (Q2).

P.III Álvarez-Marín, A., Velázquez-Iturbide, J.Á., and Castillo-Vergara, M. (2020). Intention to use an interactive AR app for engineering education. In 2020 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct), 70-73. doi: 10.1109/ISMAR-Adjunct51615.2020.00033. CORE A* (Computing Research and Education Association of Australasia Conference Ranking).

P.IV Álvarez-Marín, A., Velázquez-Iturbide, J.Á., and Castillo-Vergara, M. (2021). The acceptance of augmented reality in engineering education: The role of technology optimism and technology innovativeness. In Interactive Learning Environments. doi: 10.1080/10494820.2021.1928710. JCR 2021: 4,97 - Education & Educational Research (Q1); SJR 2021: 1,17 - Computer Science Applications (Q1).

P.V Álvarez-Marín, A., Velázquez-Iturbide, J.Á., and Castillo-Vergara, M. (2021). Technology acceptance of an interactive augmented reality app on resistive circuits for engineering students. In Electronics, 10(11), 1286. doi: 10.3390/electronics10111286. JCR 2021: 2,69 - Computer Science, Information Systems (Q3); SJR 2021: 0,59 - Computer Networks and Communications (Q2).

Publication P.I present a systematic review of the state of the art of augmented reality technology application in engineering education. This work seeks to understand the current state of augmented reality use in engineering education, identify weaknesses and strengths, pinpoint areas requiring further research, and guide researchers and developers in improving the effectiveness of current approaches.

Publication P.II presents the development of an augmented reality application for analyzing direct current (DC) in resistive circuits. This application allows interaction with elements such as batteries, bulbs, and resistors in resistive electrical circuits arranged in series and parallel. It displays real-time current intensity and voltage across each component. This application was used to determine the intent to use and the variables influencing the acceptance of this technology.

Publication P.III proposes determining the intent to use augmented reality technology among engineering students. This part of the study involved students who used the application autonomously and others who participated in a guided in-person session.

Publication P.IV proposes to determine whether subjective norm, technology optimism, and technology innovativeness can explain and predict the use of augmented reality in engineering education. This work presents a model that includes the variables mentioned above. The experiment was conducted online with a sample of 173 students.

Publication P.V proposes to determine the technological acceptance of augmented reality technology among engineering students. This work presents an extended TAM model incorporating subjective norms, technology optimism, technology innovativeness, perceived ease of use, and perceived usefulness. The experiment was conducted in person with a sample of 190 students.

In all publications, P.I – P.V, the author of this thesis, was responsible for writing the manuscripts, developing the models, developing the augmented reality application, and conducting the experiments. The co-authors contributed suggestions in the following stages: conceptualization, methodologies, formal analysis, writing, and review.

Chapter 1: Introduction

In recent years, emerging technologies have provided new opportunities for the educational sector, improving, among other aspects, academic performance (Akçayir et al., 2016), as they offer the chance to learn more efficiently and effectively through student-centered teaching methods (Al-Maroof & Al-Emran, 2018). One such technology is Augmented Reality (AR), which allows the integration of virtual objects, often in three dimensions (3D), with real-world scenarios in real-time (Billinghurst & Duenser, 2012). This technology also enables the display of additional information in a given context (Azuma, 1997) or instructions to help carry out a process (Feiner et al., 1993). While Virtual Reality (VR) technology completely immerses the user in a virtual environment, augmented reality complements reality rather than completely replacing it (Azuma et al., 2001).

The use of augmented reality technology in the classroom has led to more active participation by students (Matcha & Rambli, 2012), increasing their interest and motivation to learn (Ayala Alvarez et al., 2017) and contributing to improving their learning experience. This technology has also increased students' academic performance due to its ability to enable a rapid understanding of spatial problems and complex relationships (Cheng et al., 2018).

Consequently, augmented reality can be considered a promising technology for engineering education, as it can aid in learning complex structures and behaviors with non-visible properties found in this discipline (Nesterov Aleksandr et al., 2017). Additionally, incorporating this technology in this disciplinary area may enhance the capabilities of future engineers to join the increasingly digitalized and optimized operations integrated into networks under the concept of Industrial Augmented Reality (IAR) (Fraga-Lamas et al., 2018). It is important to note that IAR is one of the key technologies identified by new industry 4.0 paradigms to improve industrial processes and maximize worker efficiency

(Vidal-Balea et al., 2020), so incorporating this technology in engineering education could not only affect the academic performance of students in the short term but also provide them with long-term skills to successfully enter an increasingly digitalized labor market.

One area of engineering where augmented reality has been used for teaching is electronics. Students find some concepts difficult to understand, such as electricity, since its behavior is not visible in electrical circuits (Matcha & Rambli, 2012). Therefore, making electricity visible through augmented reality applications makes this subject more comprehensible and helps students better understand these concepts (Restivo et al., 2014).

However, despite the benefits demonstrated by these innovative technologies, more studies need to analyze their acceptance by users (Rodrigues et al., 2019). Furthermore, the technological acceptance of augmented reality among students remains unexplored, crucial for its successful implementation in the educational process. Understanding these dynamics will help clarify these users' behaviors with this technology (Esteban-Millat et al., 2018).

With all this background in view, the main research question of this thesis is as follows:

What variables influence engineering students' acceptance of augmented reality technology in their educational process?

Therefore, the main objective of the thesis presented is to propose a model of acceptance of augmented reality technology, which includes the variables that affect students' acceptance of its use in the context of learning electrical circuits in engineering. Understanding these variables should allow university academics and higher education institutions to establish policies to encourage the educational use of this technology to benefit students' academic performance.

Next, section 1.1 presents the motivation for conducting the research in this thesis, section 1.2 proposes the objectives, research questions, and hypotheses, section 1.3 outlines the main contributions that arise from this study, and section 1.4 summarizes the thesis chapters.

1.1 Motivation

Two motivations drive the development of this doctoral thesis. The first is to develop an application using cutting-edge technology to support engineering students' teaching and learning processes. The focus was on electromagnetism, more specifically electrical circuits, due to students' difficulty understanding concepts related to electricity (Matcha & Rambli, 2012), as its behavior is invisible. In addition to improving student academic performance, augmented reality can positively affect students' attitudes towards this subject due to their participation in more playful classroom activities.

The second motivation for conducting this thesis is to incorporate augmented reality technology into the activities of future engineers. It is part of the wide range of technologies associated with Industry 4.0 and digital transformation (Vidal-Balea et al., 2020). If students incorporate these technologies early in their university education, they will have more outstanding competencies when they enter the workforce.

However, augmented reality can only be used effectively if students intend to use these technologies and if universities understand the advantages of integrating them into their learning environment (Lima et al., 2022).

1.2 Objectives, Research Questions, and Hypotheses

Considering the problem to be resolved and the motivations presented, the main research question (RQ) addressed in the included publications (P.I – P.V) is: What variables influence engineering students to accept the incorporation of augmented reality technology in their training? The following objectives, research questions, and hypotheses associated with each research chapter have been proposed to answer this question.

For the first part of the research (P.I), the following objective and research questions were posed:

O_I	:	Understand the state of the art of using augmented reality technology in engineering education.
RQ_{I-1}	:	In which engineering studies has AR been applied?
RQ_{I-2}	:	In what types of educational activities in engineering education have AR apps been used?
RQ_{I-3}	:	How have AR apps been assessed in engineering education?
RQ_{I-4}	:	What are the main characteristics of the AR apps used in engineering education?
RQ_{I-5}	:	What is the degree of interactivity of the AR apps used in engineering education?

To evaluate the models proposed later, it was necessary to meet the following two objectives:

O_{II} : Develop an augmented reality application.

O_{III} : Determine the intention to use the developed application.

First, the study aimed to develop an AR application that analyzes resistive electrical circuits (in series and parallel). This application allowed interaction with batteries, bulbs, and resistors, displaying the current intensity and voltage in real-time in each circuit component (P.II), to later measure the intention of use by students of this application (P.III).

Subsequently, the following stages were undertaken. Thus, the objective and hypotheses proposed for the next part of the research (P.IV) are as follows:

O_{IV} : Analyze the role that technological optimism and innovation play in accepting augmented reality technology in engineering education.

H_{IV-1} : Subjective norm has a positive effect on technology optimism.

H_{IV-2} : Subjective norm has a positive effect on technology innovativeness.

H_{IV-3} : Technology optimism has a positive effect on technology innovativeness.

H_{IV-4} : Technology optimism has a positive effect on attitude toward using.

H_{IV-5} : Technology innovativeness has a positive effect on attitude toward using.

H_{IV-6} : Attitude toward using has a positive effect on behavioral intention to use.

The motivations and justifications for the hypotheses raised can be found extensively in publication P.IV. This part of the research was conducted online, using the application autonomously by the students. The proposed model is shown in Figure 1.

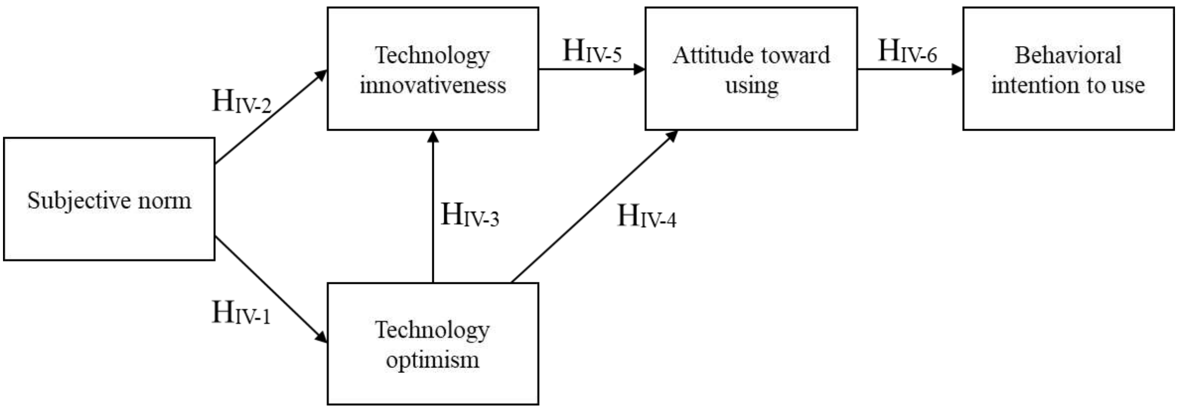

Figure 1: First proposed model: Online evaluation.

Finally, for the last part of the research (P.V), the following objective and its respective hypotheses were proposed, presented below:

O_V	:	Determine the variables that can explain and predict engineering students' use of this technology.
H_{V-1}	:	Subjective norm has a positive effect on technology optimism.
H_{V-2}	:	Subjective norm has a positive effect on technology innovativeness.
H_{V-3}	:	Technology optimism has a positive effect on technology innovativeness.
H_{V-4}	:	Technology optimism has a positive effect on perceived usefulness.
H_{V-5}	:	Technology optimism has a positive effect on attitude toward using.
H_{V-6}	:	Technology innovativeness has a positive effect on attitude toward using.
H_{V-7}	:	Perceived ease of use has a positive effect on perceived usefulness.
H_{V-8}	:	Perceived ease of use has a positive effect on attitude toward using.
H_{V-9}	:	Perceived usefulness has a positive effect on attitude toward using.
H_{V-10}	:	Attitude toward using has a positive effect on behavioral intention to use.

In publication P.V, the motivations and justifications for each of the hypotheses raised are found. In this part of the research, a guided face-to-face evaluation was proposed. The model proposed in this case is shown in Figure 2.

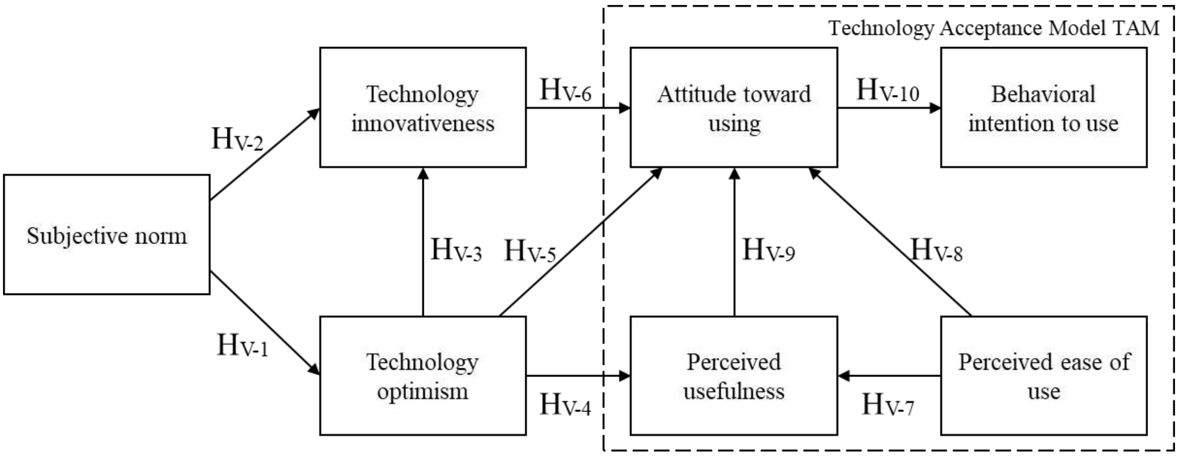

Figure 2: Second proposed model: Face-to-face evaluation.

1.3 Contributions

The main contributions of this compendium thesis are the following, corresponding to the five previously mentioned publications:

C_1 : A review of the state of the art of using augmented reality technology in engineering. It includes identifying this technology's strengths and weaknesses, areas where more research is required, and suggestions for researchers and application developers to improve effectiveness in its implementation. This contribution is presented in P.I.

C_2 : An application developed with augmented reality technology and a high degree of interactivity supports engineering students' electronics learning. This contribution is presented in P.II.

C_3 : The intention to use the developed application was evaluated through an autonomous online evaluation by 190 students and a guided face-to-face evaluation with 124 students. In both cases, the application shows a high intention of use. This contribution is presented in P.III.

C_4 : A validated technological acceptance model of augmented reality determines the role of technological optimism and technological innovation in accepting this technology, which had not been investigated in the context of augmented reality applications. This study involved a sample of 173 students. This contribution is presented in P.IV.

C_5 : A validated, extended TAM model of technological acceptance of augmented reality, whose results could guide academics and higher education executives in incorporating this technology into educational processes. This part of the study involved a sample of 190 students. This contribution is presented in P.V.

Overall, the theoretical contributions of this thesis are two models of acceptance of augmented reality technology in two different contexts to explore the factors that could influence the intention to use augmented reality technology by engineering students. On the other hand, the practical implications of these results, in addition to the development of an augmented reality application that can be used for learning electrical circuits, was to provide input to higher education institutions so that they can encourage their students and the entire educational ecosystem to use emerging technologies in the teaching-learning process.

1.4 Document Structure

This compendium thesis comprises five chapters and includes five publications: P.I – P.V. The content of each chapter is summarized below:

Chapter 1	:	This chapter presents the thesis's introduction and motivation, including the research questions, hypotheses, and objectives proposed, as well as the contributions made.
Chapter 2	:	An overview of the state of the art of using augmented reality technology in the education of future engineers is presented, along with studies conducted to analyze the factors that can influence the acceptance of augmented reality technology in its use.
Chapter 3	:	This chapter introduces the methodologies used in the systematic review and in constructing and validating the proposed technological acceptance models.
Chapter 4	:	The results of this thesis are presented. The main results published in P.I – P.V are displayed and discussed, as are the general contributions of the study.
Chapter 5	:	The final chapter presents the general conclusions of this doctoral thesis and proposes future studies.

Chapter 2: Literature Review

Augmented reality is an emerging technology that has demonstrated its potential in various fields, including education. Specifically, its application in the education of future engineers has attracted considerable interest due to its ability to enhance the understanding and retention of knowledge in specific subject areas.

This chapter summarizes the state of the art of using augmented reality technology in education and identifies existing technological acceptance models and their application to this particular technology.

2.1 Augmented Reality in Education

Over the past decade, augmented reality applications have become increasingly popular. Many user experiences and experiments have been in different areas, including education (Dey et al., 2018).

Various systematic reviews on the use of augmented reality in education have been conducted, both generally (Akçayır & Akçayır, 2017; Bacca et al., 2014; da Silva et al., 2019; Ibáñez & Delgado-Kloos, 2018; Pellas et al., 2019) and in specific fields, such as for training surgical procedures in medicine (Barsom et al., 2016; Guha et al., 2017; Meola et al., 2017; Pelargos et al., 2017; Yoon et al., 2018). Systematic reviews have also been conducted on the use of augmented reality in industrial maintenance operations (Palmarini et al., 2018) and on the usability of augmented reality applications (Dey et al., 2018).

Five systematic reviews of augmented reality in educational areas are briefly discussed below.

The first study (Bacca et al., 2014) investigates the uses, advantages, limitations, effectiveness, challenges, and features of augmented reality in educational settings. The main goal of these augmented reality applications has been to explain a topic of interest, providing additional information. It has effectively improved students' academic performance, motivation, engagement, and positive attitudes. The study also identifies some limitations of the technology, including difficulties in maintaining overlaid information, paying too much attention to virtual information, and considering augmented reality as an invasive technology.

The second study aims to analyze the use and advantages of augmented reality technologies in educational settings (Akçayır & Akçayır, 2017). The most frequently reported advantage of this technology is the promotion of improvements in learning achievement. Some highlighted challenges include its usability and frequent technical problems.

The third study in science, technology, engineering, and mathematics (STEM) seeks to determine the characteristics of educational augmented reality applications, their associated instructional processes, and the observed learning outcomes (Ibáñez & Delgado-Kloos, 2018). This study concludes that augmented reality applications should contain features to acquire the necessary competencies of the STEM disciplines and provide metacognitive scaffolding and experimental support for research-based learning activities.

The fourth study is a systematic review of the evaluation of augmented reality tools for education (da Silva et al., 2019). Most results (including those of learning outcomes and usability) are positive. However, most studies need the incorporation of the teacher as an instructional designer and the use of multiple metrics to evaluate educational gains.

The fifth study addresses augmented reality through game-based learning in primary and secondary education (Pellas et al., 2019). This study concludes that this technology can influence students' skill acquisition, transfer knowledge, increase their interest in subjects, and improve their digital skills.

All five studies suggest further deepening research on the effects of augmented reality applications on knowledge construction. They also recommend exploring the learning processes in different educational environments and with diverse student populations. In general, augmented reality in education comprises exploration applications (e.g., augmented books) and games (Ibáñez & Delgado-Kloos, 2018). In this last aspect, game-based learning has quickly gained momentum by enabling new teaching approaches in primary and secondary education (Pellas et al., 2019).

On the other hand, engineering deals with designing and constructing artificial artifacts. Understanding such artifacts takes work, as they can have complex three-dimensional structures with non-visible properties. Augmented reality technology has the potential to help understand the structure and behavior of such artifacts. Therefore, augmented reality can be considered a promising technology for engineering education (Nesterov Aleksandr et al., 2017).

2.2 Technological Acceptance

Personality traits and social attitudes explain and predict human behavior (Ajzen, 1991). A person's behavior is based on relevant information and beliefs. While a person may have many beliefs about a given behavior, only a few may influence them (Miller, 1956). The above also applies to people's relationships with technology.

Technological acceptance aims to specifically explain a person's behavior toward using computer systems (Davis et al., 1989). It is related to the intention to use, defined as the subjective probability that a person will carry out a specific behavior (Fishbein & Ajzen, 1975). When the situation gives the person complete control over their behavioral performance, the intention to use alone should be sufficient to predict behavior (Ajzen, 1991).

Below are the most important models for predicting or explaining people's behavior in adopting information technologies.

Davis, in 1986, proposed the Technology Acceptance Model (TAM) (Davis, 1986; Davis et al., 1989) (Figure 3) as an adaptation of the Theory of Reasoned Action (TRA), a model proposed to specifically explain behavior in the use of computer systems (Fishbein & Ajzen, 1975). The theory of reasoned action explains the intention to use through attitude towards using and subjective norm. However, the technology acceptance model proposed that subjective norms would not directly influence attitudes toward using. The attitude towards using, as well as use, could be explained by perceived ease of use and perceived usefulness. Two extensions to the model have subsequently been proposed: TAM 2

(Venkatesh & Davis, 2000) (Figure 4) and TAM 3 (Venkatesh & Bala, 2008) (Figure 5), which incorporate other factors to explain better the intention to use.

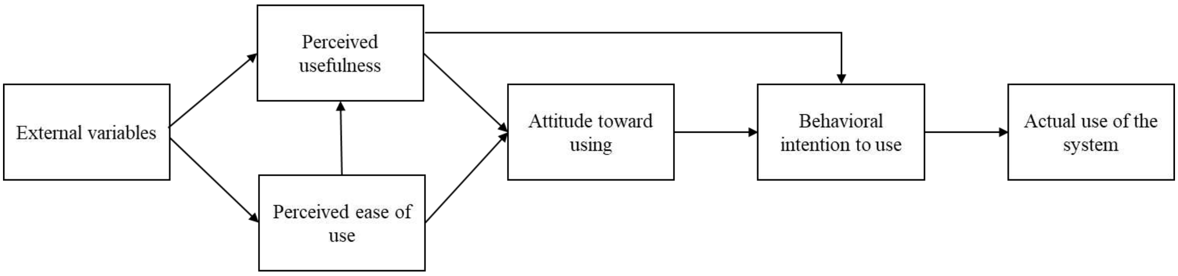

Figure 3: TAM model.

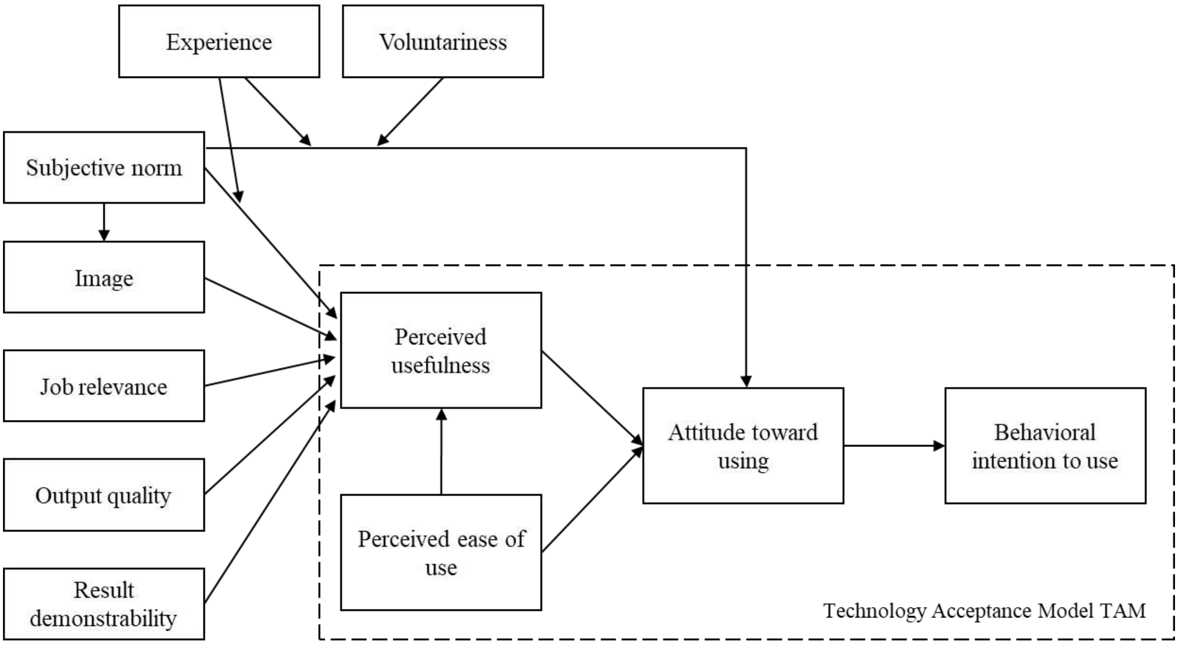

Figure 4: TAM 2 model.

Parasuraman proposed the Technology Readiness (TR) Model (Figure 6) to explain technological acceptance (Parasuraman, 2000). This model consists of four dimensions: technological optimism and technology innovativeness as drivers of technological readiness, while discomfort and insecurity are indicated as inhibiting elements. However, subsequent studies suggest that technological optimism and innovativeness are stable individual dimensions for measuring technology readiness (Berger, 2009; Liljander et al., 2006; Taylor et al., 2002).

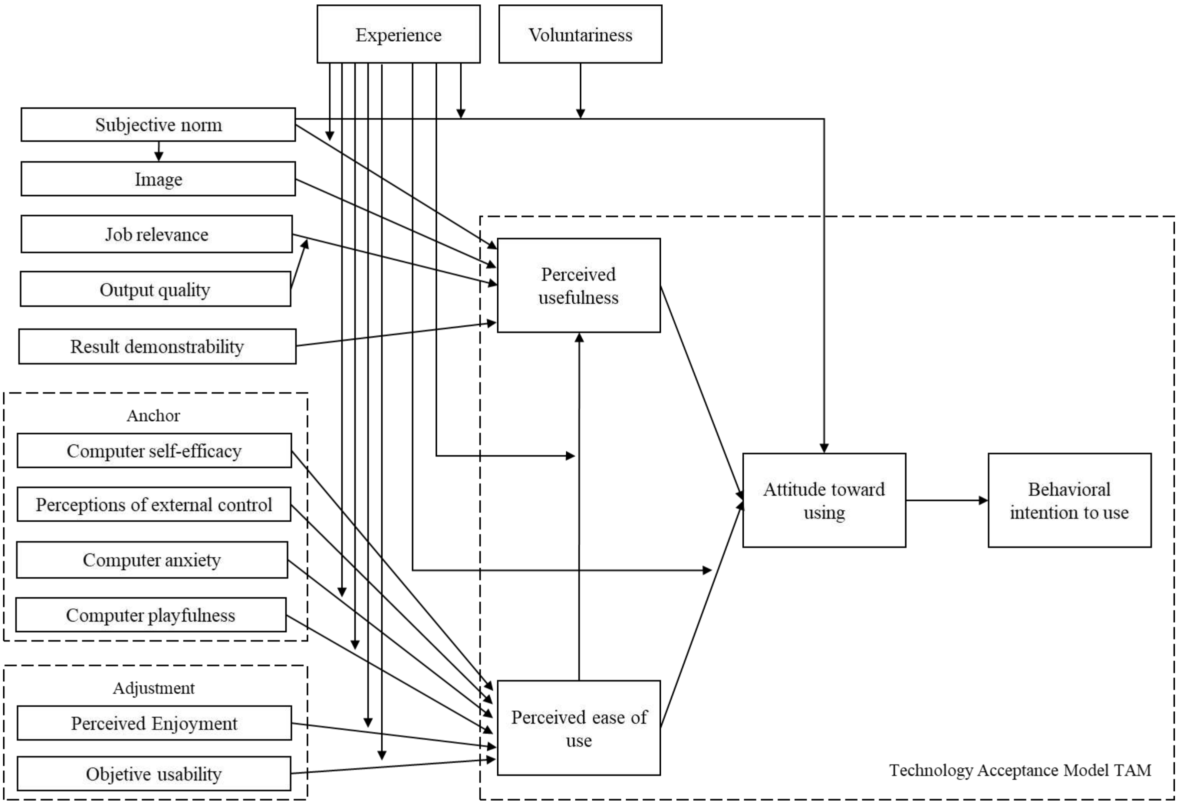

Figure 5: TAM 3 model.

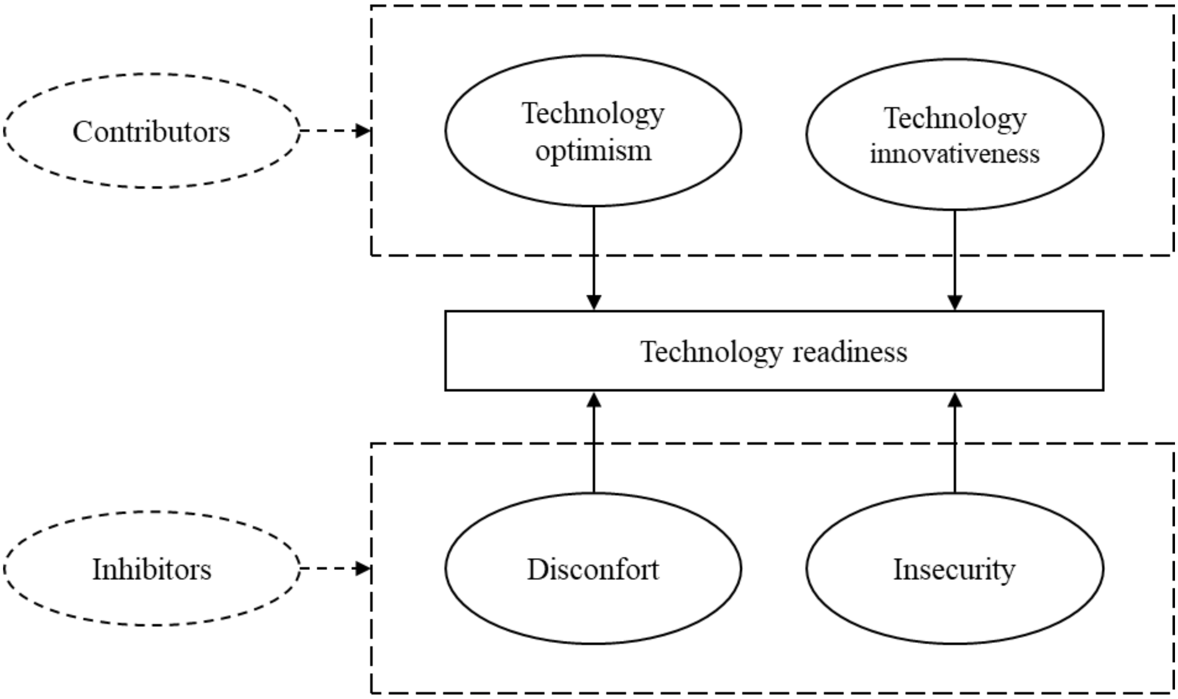

Figure 6: TR model.

Venkatesh et al. proposed the Unified Theory of Acceptance and Use of Technology (UTAUT) in 2003 (Venkatesh et al., 2003) (Figure 7) and an extension of this model, UTAUT 2, in 2012 (Venkatesh et al., 2012) (Figure 8). These models were developed to integrate several existing models.

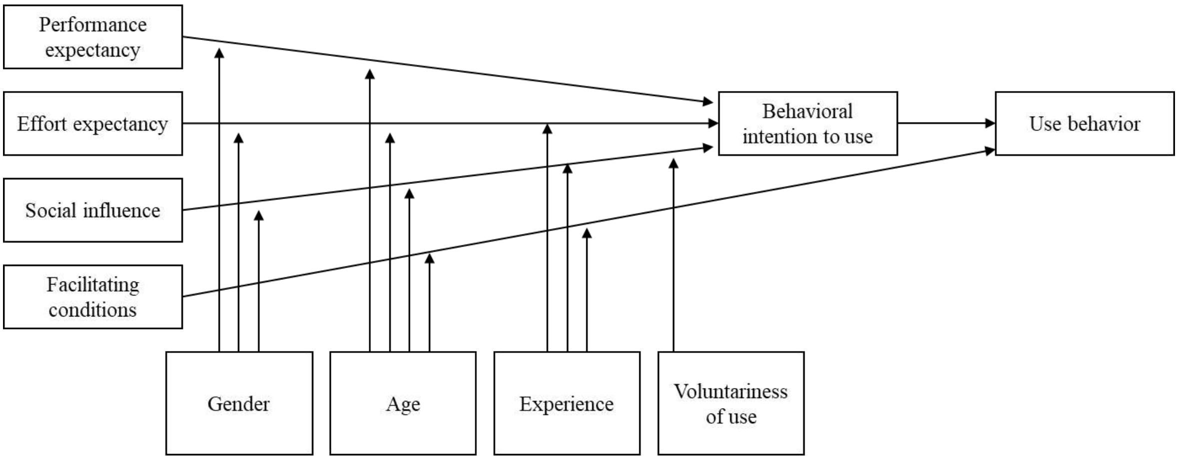

Figure 7: UTAUT model.

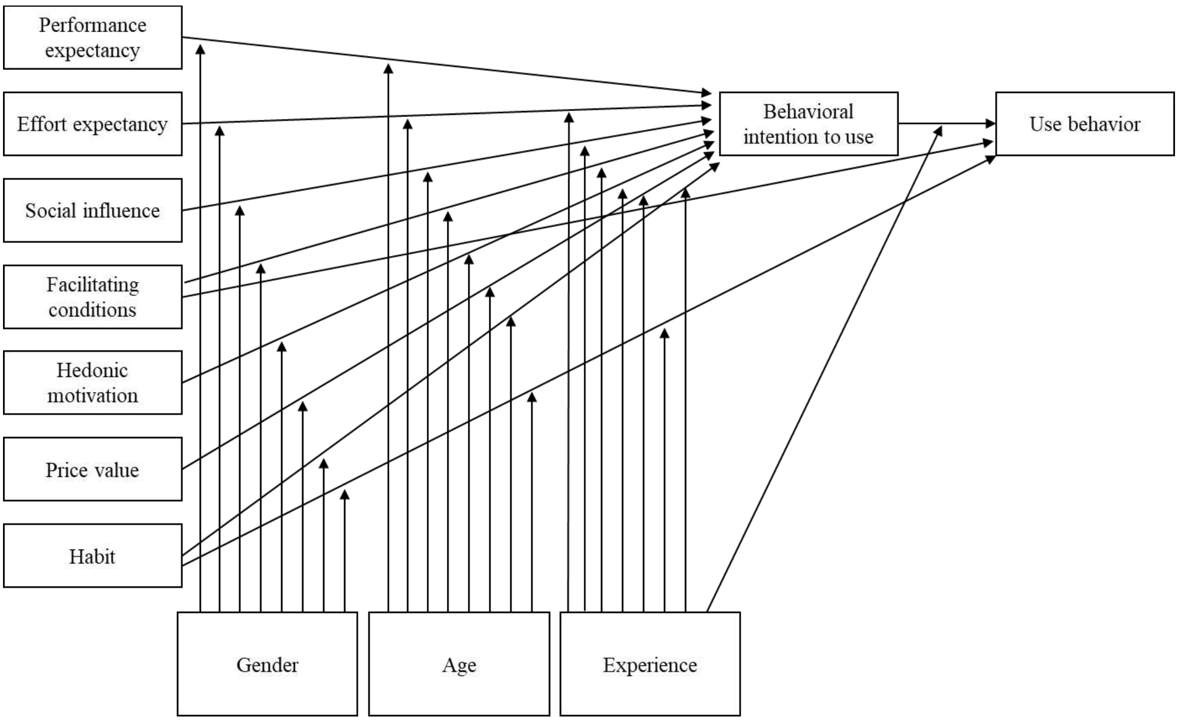

Figure 8: UTAUT 2 model.

In 2007, Lin, Shih, and Sher proposed the Technology Readiness and Acceptance Model (TRAM) (C.-H. Lin et al., 2007) (Figure 9), which incorporated the Technology Readiness (TR) model as a construct within the Technology Acceptance Model (TAM).

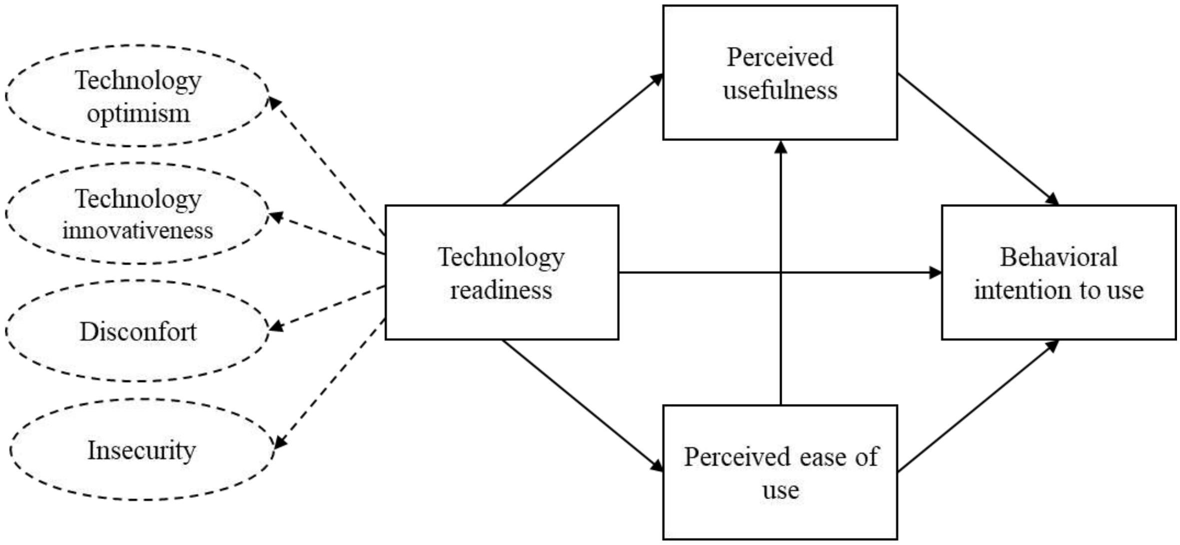

Figure 9: TRAM model.

Two models have been proposed for virtual and augmented reality technologies. Oh and Yoon introduced the Haptic Enabling Technology Acceptance Model (HE-TAM) (Oh & Yoon, 2014) (Figure 10), which combines the Technology Acceptance Model (TAM) with the Innovation and Diffusion Theory (IDT) (Rogers, 1983). This new model incorporates the construct of presence as an experience mediated by virtual reality.

Finally, Alqahtani and Kavakli in 2017 proposed the Augmented Reality Technology Acceptance Framework (ART) (Alqahtani & Kavakli, 2017) (Figure 11), which integrates the Unified Theory of Acceptance and Use of Technology (UTAUT) with the Information Systems Success Factors and Motivation Theory (IS Success Factors and Motivation Theory) (DeLone & McLean, 1992). This model incorporates, among other constructs, the quality of information and the system to explain their satisfaction and usage. It focuses on the system's characteristics, rather than on the characteristics of the people who would use the system, to explain the intention to use it.

Previous studies have questioned the capability of the Technology Acceptance Model (TAM) to explain new scenarios. However, these studies focus on commercial applications, especially in the field of marketing and the perceived value of augmented reality applications. A recent study investigating the use of an augmented reality application in tourism (Vishwakarma et al., 2020) suggests that the applicability of TAM is limited since it only considers adoption from the user's perspective rather than from the consumer's. The authors proposed the Value-based Adoption Model (VAM) (Figure 12) to address this issue (Kim et al., 2007), considering adoption from the consumer's perspective.

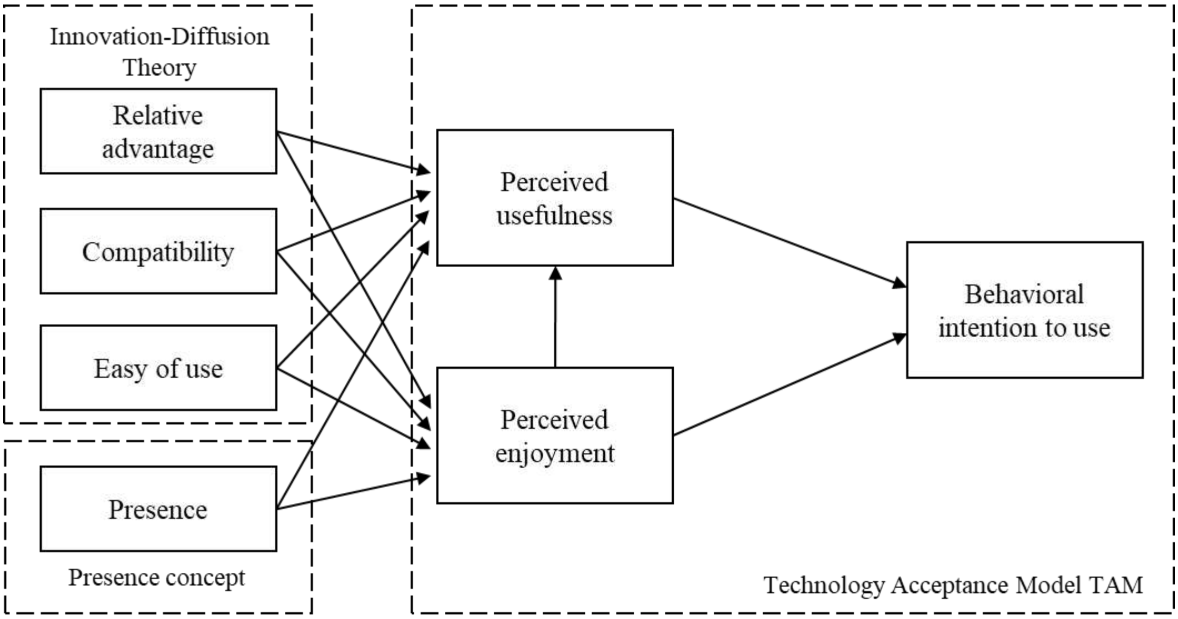

Figure 10: HE-TAM model.

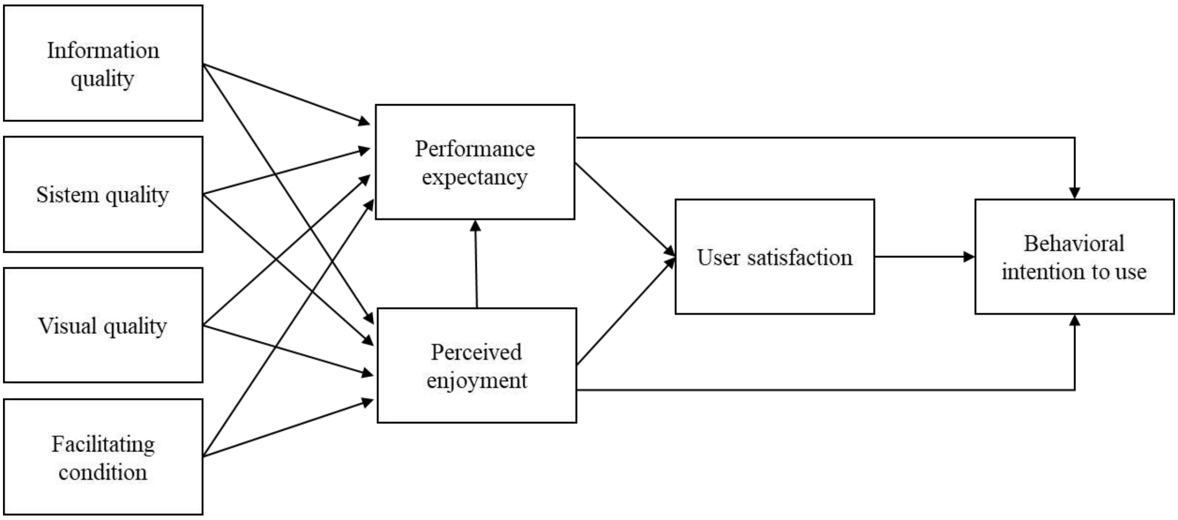

Figure 11: ART model.

However, it has been demonstrated that extended versions of the TAM remain valid in the educational field, where applications are used to support the educational process and autonomous learning. The above is because, in this context, students are not considered consumers since educational applications are not marketed. Evidence of this is that in recent years, TAM has been applied in various studies within the educational sector, such as in sciences (Cabero-Almenara et al., 2019), geometry (Pittalis, 2020), MOOCs (Massive

Online Open Courses) (Al-Adwan, 2020; Virani et al., 2020), e-learning (Hanif et al., 2018; Kuliya & Usman, 2021), mobile learning (Pratama, 2021; Qashou, 2021; Shodipe & Ohanu, 2021), digital communication (Al-Rahmi et al., 2020), and the use of open-source software (Racero et al., 2020).

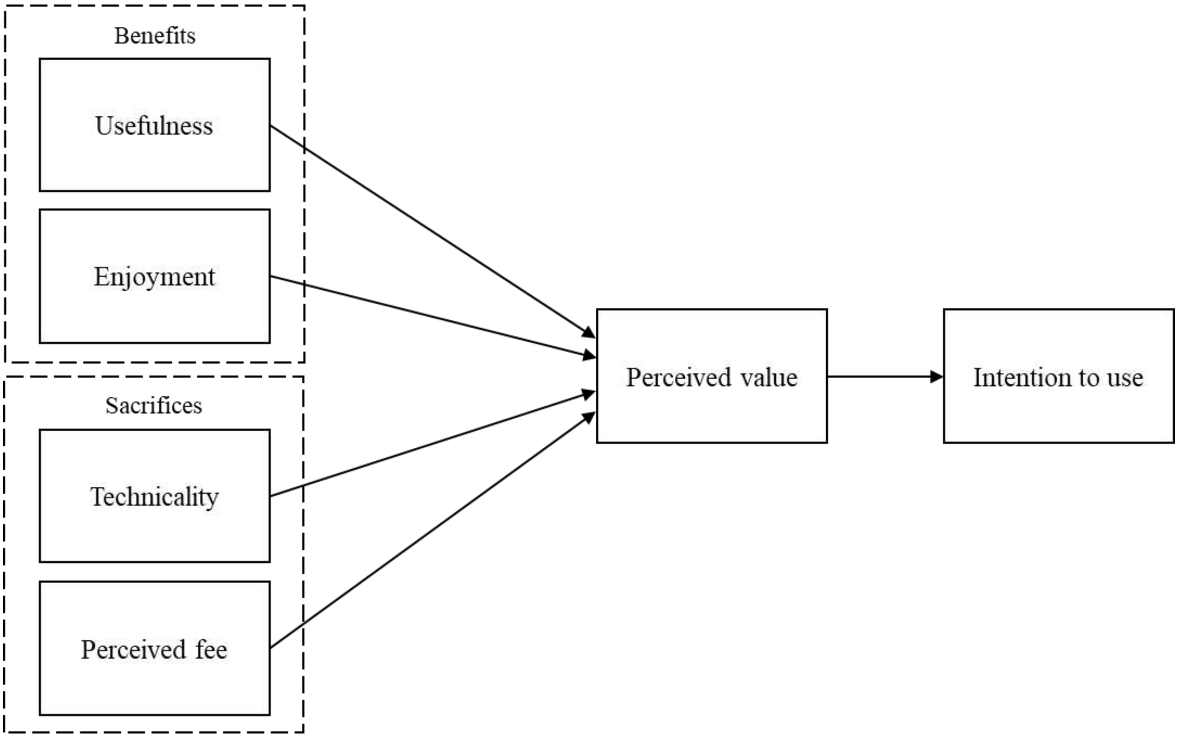

Figure 12: VAM model.

In engineering education, only one study has addressed the acceptance of augmented reality technology. This study used the TAM model to investigate students' perceptions regarding problem-solving in electromagnetism (Ibáñez et al., 2016). The evaluation results indicated that the behavioral intention to use augmented reality technology was related to perceived enjoyment. However, the perceived usefulness variable had to be excluded due to the lack of consistency in student responses. Personal or environmental characteristics of students were not considered in this study.

Chapter 3: Methodology

Two methodologies were employed in the development of this doctoral thesis. The first was a systematic review of the state of the art, and the second was an analysis of the factors influencing the technological acceptance of augmented reality. Below, each of these is detailed.

3.1 Methodology for Systematic Review

In this part of the study (P.I), the methodology proposed by Kitchenham (Kitchenham, 2004) was adapted and used.

A. Research Questions

The following five research questions were formulated regarding augmented reality in engineering education:

RQ_{I-1}: In which engineering studies have AR been applied?

RQ_{I-2}: In what types of educational activities in engineering education have AR apps been used?

RQ_{I-3}: How have AR apps been assessed in engineering education?

RQ_{I-4}: What are the main characteristics of the AR apps used in engineering education?

RQ_{I-5}: What is the degree of interactivity of the AR apps used in engineering education?

B. Documentation Sources

To identify relevant literature, four representative online research databases in engineering education were used: 1) Web of Science, 2) Scopus, 3) ACM Digital Library, and 4) IEEE

Xplore Digital Library. Their extensive coverage of published conference proceedings was critical in selecting these databases (Meho & Rogers, 2008).

C. Search Terms

The following search strings were used: "engineering education" and "augmented reality." The string must appear in each publication's title, abstract, or keywords.

D. Study Selection

A set of inclusion and exclusion criteria was adopted based on the criteria used in some of the reviews mentioned earlier (Akçayır & Akçayır, 2017; Ibáñez & Delgado-Kloos, 2018), as shown in Table 1.

Table 1: Inclusion and exclusion criteria

Inclusion criteria	**Exclusion criteria**
(a) Any year of publication. (b) Journal article or conference paper. (c) Reporting empirical research. (d) Used in engineering education. (e) AR is the leading technological component.	(a) Citing the term "augmented reality" but dealing with "virtual reality." (b) Used for training (e.g., professional learning). (c) Emphasizing app design or development as opposed to educational use or evaluation.

In the initial search, 732 publications were found. These were analyzed to discard duplicates, resulting in 583 unique publications. After removing those not available in full text, 523 remained. Subsequently, inclusion and exclusion criteria were applied, leaving 56 publications. Finally, studies were discarded that, despite having the same authors, had a similar focus, so the final analysis centered on 52 publications.

E. Analysis Methodology

The analysis procedure needs to be revised to ensure the validity and integrity of the results (DeFranco & Laplante, 2017). Therefore, the selected articles were qualitatively analyzed, considering the relationship between content and context (Elo & Kyngäs, 2008; Hsieh & Shannon, 2005).

The analysis and classification process aimed to answer the five research questions and involved several iterations. The process stopped when a consensus was reached among the authors. The primary source of disagreement among the authors was dissatisfaction with the resulting categories.

For RQ_{I-1} (knowledge areas), RQ_{I-2} (educational activities), and RQ_{I-5} (interaction characteristics), categorization was relatively straightforward based on the analyzed studies.

For RQ_{I-3} (impact evaluation), two relevant issues were identified. The first issue was identifying the educational criteria evaluated in the publications. The second issue arose from the finding that most studies evaluated the subjective perception of students or teachers regarding augmented reality technology. Here, the analysis continued to determine the variables measured in these studies. Studies were analyzed without predefined categories through several iterations (Glaser & Strauss, 2017). The identification or definition of measured variables was based on the descriptions of the examined studies. Once the variables were identified, their correspondence with each study was analyzed. In the case of academic performance, a case-by-case analysis of the results was conducted.

For RQ_{I-4} (application characteristics), a search was conducted for relevant classifications that could inspire the analysis. Two informative classifications were identified. The first classification identified the enabling technologies used in augmented reality (Wang et al., 2013). The second classification analyzed the functional characteristics of the applications (Hugues et al., 2011).

3.2 Methodology for the Technological Acceptance Study

In this part of the study, an augmented reality application specially developed for this purpose was used (P.II), and its intention to use was determined (P.III). Below are the procedures and samples used and the data analysis techniques performed.

A. Procedure and Sample

Students were invited via email to participate in the online evaluation (P.IV). A three-minute video explaining the use of the application was shown. Then, links were shared to download the application from Google Play (for Android systems) and the APP Store (for iOS systems). Students were able to use the application freely. Afterward, they were asked to complete the survey. The sample for this case consisted of 173 students.

The face-to-face evaluation (P.V) was conducted in a guided session with the students. The survey and the experience were carried out in a tablet-equipped laboratory. Initially, a three-minute video demonstrated how the interactive augmented reality application worked. Then, the students spent 30 minutes interacting with the application, performing various guided exercises like other studies on the acceptance of this technology in education (Ibáñez et al., 2016; Miranda Bojórquez et al., 2016; Wojciechowski & Cellary, 2013) and in other fields (Pantano et al., 2017; Voinea et al., 2020). The students analyzed different current intensity behaviors while practicing with circuits in series or parallel and changing voltage and resistance values.

Additionally, the students were able to interact freely with the application. At the end of the experience, a survey was conducted. This time, the sample consisted of 190 students.

For both studies, the convenience sampling method was used, a non-probabilistic sampling technique that involves selecting the sample from a population that is easy to reach or contact. This type of sampling is useful for pilot tests. Student participation was voluntary and not associated with assessment, and no extra points were offered for participating in the study. Furthermore, anonymity and strict confidentiality of data were guaranteed. Pilot tests such as those conducted in the development of this thesis have previously been used to determine the behavioral intention in augmented reality applications (Cabero-Almenara et al., 2019; Ibili et al., 2019; Jung et al., 2018; Lee et al., 2017; Pantano et al., 2017; Rese et al., 2017; Voinea et al., 2020).

B. Data Analysis

Simultaneous tests were conducted on the models and hypotheses proposed (P.IV and P.V) using structural equation modeling through the Partial Least Squares (PLS) method, utilizing the software Smart PLS 3.2.9 © (Ringle et al., 2015).

The PLS technique was chosen because it combines unobserved variables representing theoretical concepts and measurement data, which provide evidence of the relationships between latent variables (Williams et al., 2009). This method is suitable because the approach includes complex models and composite variables (Sarstedt et al., 2016).

The application of the PLS technique consists of different steps, the first of which is adjusting the model (Barclay et al., 1995). The fit test is conducted for the estimated model using a resampling process of 5,000 subsamples (Henseler et al., 2016). The measurement model is evaluated, and the model fit is analyzed (Müller et al., 2018). Type B composite variables were considered for this model (Cepeda-Carrion et al., 2019).

A literature review was conducted to determine the surveys for both studies. Questionnaires from previous studies were used, as these questions had been previously validated.

For the research related to the determination of technological acceptance through an online evaluation (P.IV), a survey consisting of 15 questions was used for data collection. Table 2 presents the studies used to adapt the constructs (or latent variable, concepts not directly observable or measurable) and indicators (or observed variable, variables measured in study subjects through statements or questions rated on a Likert scale).

Table 2: Studies and indicators used in online evaluation.

Construct	Study	Indicator
Subjective norm	(Teo et al., 2008)	People whose opinions I value encourage me to use new technologies. People who are important to me help me use new technologies.
Technology optimism	(Chung et al., 2015)	The products and services that use the newest technologies are much more convenient to use. I prefer to use the most advanced technology available. Technology makes my work more efficient.
Technology innovativeness	(Chang et al., 2017)	IfIfind out that there are new technologies, I look for ways to test it. Among my classmates, I am generally the first to try new technologies. I like to experiment with new technologies.
Attitude toward using	(Pantano et al., 2017)	I think using the app in classes would be positive. The app is so interesting that you want to learn more about it. It makes sense to use the app for the study of electrical circuits. The app is a good idea.
Behavioral intention to use	(Balog & Pribeanu, 2010)	I would like to have this app if I had to study electrical circuits. I would intend to use this app to learn about electrical circuits. I would recommend other students to use this app to study electrical circuits.

For the research related to determining technological acceptance through a face-to-face evaluation (P.V), the constructs and indicators from the previous study were used, and seven indicators corresponding to the constructs of Perceived ease of use and Perceived Usefulness were added (see Table 3).

Table 3: Studies and indicators incorporated for face-to-face evaluation.

Construct	**Study**	**Indicator**
Perceived ease of use	(Pantano et al., 2017)	I found the app to be very easy to use. The app was intuitive to use. Learning how to use the app was easy. Handling the app was easy.
Perceived usefulness	(Wojciechowski & Cellary, 2013)	The use of the app improves learning in the classroom. Using the app during lessons would facilitate the understanding of certain concepts. I believe that the app is helpful when learning.

Chapter 4: Results and Discussion

This chapter provides a summary of the results obtained in publications P.I – P.V to achieve the objectives set out in section 1.2. For more details, it is suggested that the publications made by this compendium thesis be extensively reviewed.

4.1 Systematic Review of Augmented Reality in Engineering Education

Here, we address the responses to each research question presented in the first study (P.I).

$RQ_{I\text{-}1}$: In which engineering studies have AR been applied?

Augmented reality technology has been most frequently applied in technical drawing and electronics. In technical drawing, as well as in construction and surveying, 3D visualizations of elements are shown to improve understanding. In electronics, greater diversity has been found in modeling electronic components with some level of interaction. The use of this technology has yet to extend to other areas of engineering education. The use of this technology is heterogeneous across the different areas of this field. An open question is whether this situation is due to the different suitability of augmented reality to the educational needs of different areas or simply a lack of interest in these. The absence of this technology in engineering areas such as computing or telecommunications could be an argument for the first hypothesis. Indeed, disciplines whose nature is virtual do not need to use augmented reality because they already utilize many virtual resources and materials on digital devices—for example, software visualization for programming or algorithms (Naps et al., 2003; Stasko et al., 1988).

In the reviewed literature, augmented reality technology explains basic concepts and skills. Although this technology could support the development of advanced skills that will be in demand in Industry 4.0, this is different. Therefore, there is a niche for more augmented reality applications in the future. Sectors that could benefit include automotive, mechanical, automation, and aerospace.

RQ_{I-2}: In what types of educational activities in engineering education have AR apps been used?

The educational activities used by augmented reality applications vary depending on the subject. They have primarily been used in electronics labs to interact with electrical circuits and in technical drawing classes to solve problems with interactive 3D visualization. In construction classes, they are used to provide supplementary information, such as notes, images, and videos. However, their use remains minor even in these areas, and more applications designed, implemented, and evaluated to suit each area are needed.

Augmented reality applications must be integrated with active learning methods to improve educational use, especially in lab activities. These methods foster collaborative learning and allow for the personalization of exercises. Additionally, these applications should be integrated with centralized learning management systems to provide real-time feedback on student performance and track their activities and difficulties.

The virtualization of large-scale activities, such as virtual labs, can be helpful in education but requires careful planning of faculty involvement and adopting student-centered pedagogical models. In summary, more research is needed to improve the integration of augmented reality in education and adapt it to each area's needs.

RQ_{I-3}: How have AR apps been assessed in engineering education?

The perception of students and teachers, as well as the academic performance of students, has been evaluated using the following methodologies: conducting comparisons between experimental and control groups; using tests before and after the experiment; a single evaluation at the end of it; comparing grades obtained in the current academic year with those obtained in previous years; and evaluating performance in different educational environments, such as physical labs, virtual reality, and augmented reality.

In general, it has been observed that augmented reality technology increases student interest and motivation and promotes active participation in learning situations. Students find the applications helpful in enhancing their academic performance and for independent work. However, they consider it necessary to explain the theory before using the applications autonomously. Teachers believe it would be helpful for students to use it from the start of the course to learn new concepts.

Students have reported technical problems in the applications, such as instability, flickering, and delays, which could be due to the novelty of the technology or insufficiently developed prototypes.

More sophisticated evaluation instruments, not just subjective surveys, are needed to evaluate variables such as ease of use, motivation, and technology acceptance. Students have evaluated their perceptions of different aspects more frequently than teachers. More studies on teachers are recommended as they are key agents in adopting educational technologies.

Spatial ability is the most commonly measured variable regarding the impact on academic performance, and augmented reality has shown a positive impact. However, more controlled evaluations are needed for more representative and generalizable results. It is also necessary to evaluate augmented reality technology in more subjects and educational approaches.

RQ_{I-4}: What are the main characteristics of the AR apps used in engineering education?

The characteristics of the applications were analyzed using two classifications. The first classification identifies five enabling technologies (Wang et al., 2013): visual representation; computational device; input media; display service; and tracking system. The most common visual representation is 3D figures. Most applications run on desktop or laptop computers, although their use on mobile devices is growing. Most augmented reality applications simultaneously use monitor-based displays, marker-based tracking, and device movement as input media.

The second classification identifies five functional characteristics (Hugues et al., 2011): augmented visibility, perceptual association with the embedding of virtual objects, documented reality, documented virtuality, and enhanced understanding. The most used functional characteristic is augmented visibility, using 3D elements to support the training of spatial skills. In the future, augmented reality applications could be improved by incorporating functional features of perceptual association and integrating virtual objects to obtain virtual elements that interact more naturally with the environment. Markerless tracking systems should also be explored more to achieve smoother interaction with the environment without the need for these.

RQ_{I-5}: What is the degree of interactivity of the AR apps used in engineering education?

Only about a quarter of the applications used in the studies have some degree of interactivity, achieving only in some cases Level III (complex interaction, the student can manipulate objects to analyze their behavior) out of a total of four levels (Aqel, 2013), and the personalization of the learning experience is minimal. Therefore, more efforts are needed to develop applications that allow higher levels of interactivity. The above would enable more enriching educational activities and allow students to participate more actively in learning.

4.2 Design of an Augmented Reality Application

An augmented reality application was developed to analyze direct current (DC) in resistive circuits (P.II). The degree of interactivity of existing applications in this subject could be higher (level III) because they only allow the manipulation of graphic objects to analyze their behavior (Matcha & Rambli, 2012; Restivo et al., 2014). Therefore, we aimed to create an application with a higher level of interactivity, featuring real-time interaction that generates a simulation in which stimuli produce complex responses (level IV) (Aqel, 2013).

The developed application offers five types of circuits—both series and parallel—to choose from. Batteries, bulbs, and resistors can be incorporated into the circuit. The circuits in the application allow for any configuration and simulate the flow of current each time batteries, bulbs, and resistors are incorporated. Users can change the voltage values of batteries and the resistance in bulbs and resistors. The application calculates and displays the resulting voltage and amperage in real time (Figure 13).

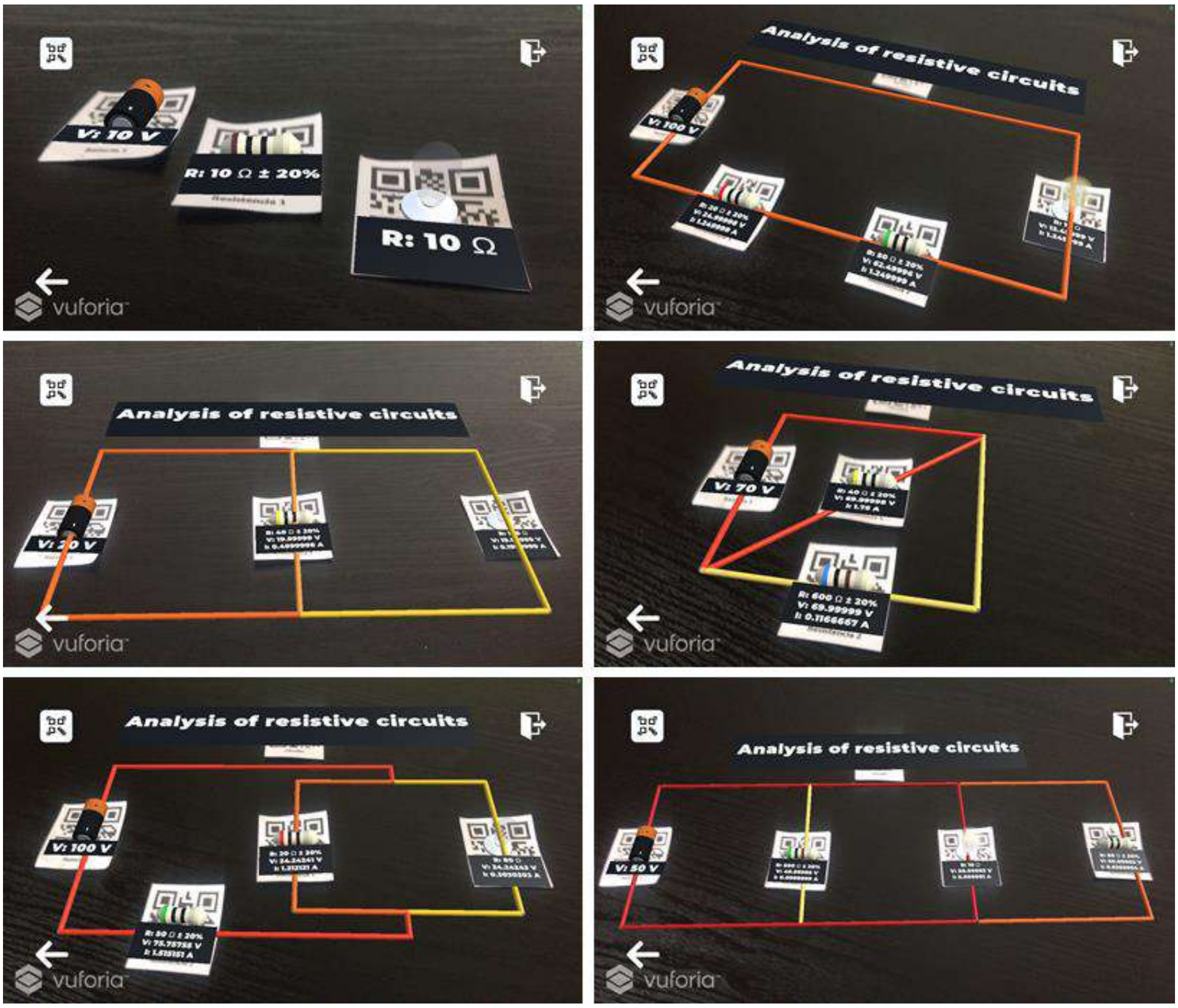

Figure 13: Interactive application developed.

The application assigns a color according to the amperage value in each circuit branch. A red branch indicates high amperage, orange indicates medium, yellow indicates low amperage, and gray indicates no amperage. The bulb's brightness depends on the amperage of the branch in which it is located.

The application calculates the current intensity and voltage values using the loop method and Kirchhoff's Voltage Law (Floyd, 2007). It utilizes an optical tracker in its operation. The circuit, batteries, bulbs, and resistors use a QR code as a target to position each figure in augmented reality in space. The application was developed in Unity 3D using the Vuforia SDK. The three-dimensional objects were created with Blender (Figure 14).

Thus, the developed application allows students to practice with a wide range of electrical circuit configurations due to its high level of interactivity. In addition to having various types of series and parallel circuits to practice with, students can freely configure them to understand the behavior of the current through the branches. Students can better understand how electricity works by interacting freely with the application. Additionally, it provides students with a tool that delivers the resulting values if they wish to develop numerical exercises.

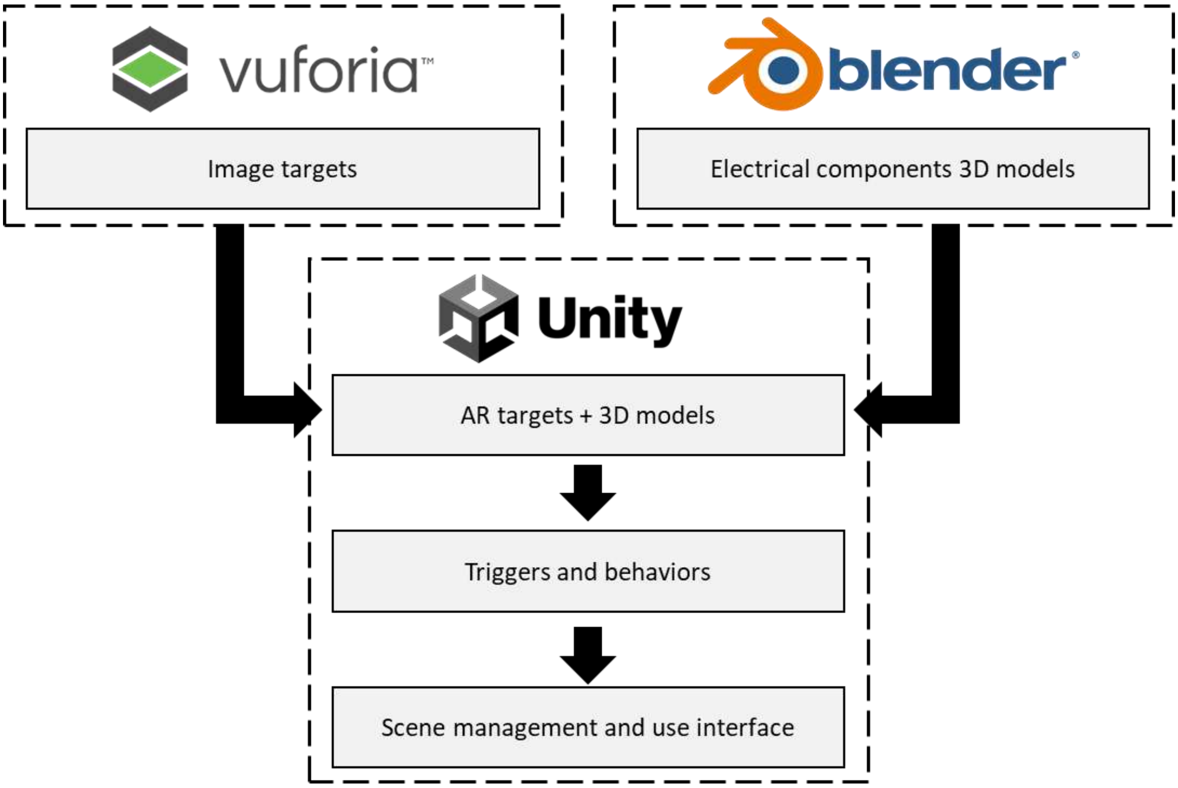

Figure 14: Developed application architecture.

Next, the attitude towards using and intention to use demonstrated by students towards the developed application (P.III) was evaluated since these variables should be sufficient to predict user behavior (Ajzen, 1991). A survey was administered to 314 students from various engineering specialties. The results showed that students exhibited a high level in both variables: attitude towards using scored 4.41, and intention to use scored 4.36 on a scale where values can range from a minimum of 1 to a maximum of 5.

4.3 The Role of Technological Optimism and Innovativeness in the Acceptance of Augmented Reality Technology in Engineering Education

Figure 15 and Table 4 show the results for the online-evaluated model (P.IV). This table also displays the path coefficients (which denote the influence that one construct has on another) obtained for each hypothesis. All of the model's hypotheses were accepted.

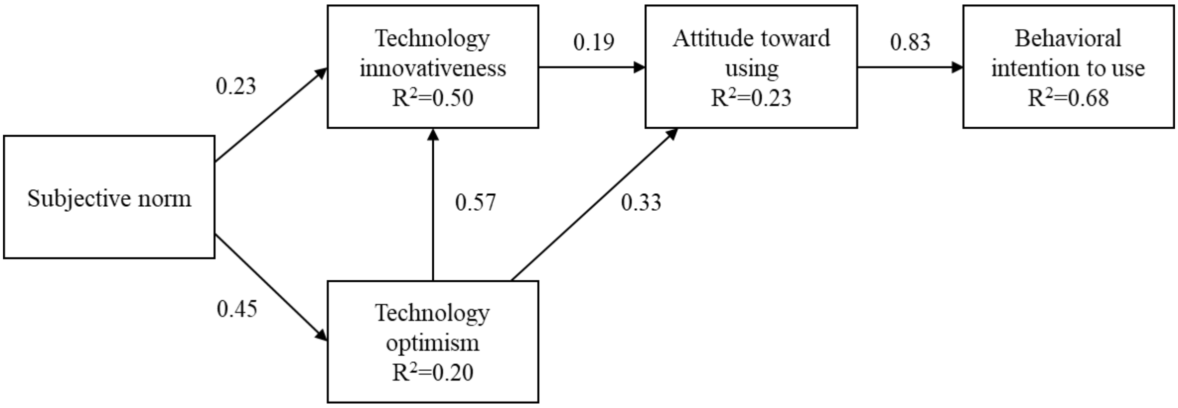

Figure 15: Research model resulting from the online evaluation.

Table 4: Results of the structural model of the online evaluation.

Hypothesis	Path	p-value	Supported
H_{IV-1}: Subjective norm → Technology optimism	0.45	0.00	Yes
H_{IV-2}: Subjective norm → Technology innovativeness	0.23	0.00	Yes
H_{IV-3}: Technology optimism → Technology innovativeness	0.57	0.00	Yes
H_{IV-4}: Technology optimism → Attitude toward using	0.33	0.00	Yes
H_{IV-5}: Technology innovativeness → Attitude toward using	0.19	0.02	Yes
H_{IV-6}: Attitude toward using → Behavioral intention to use	0.83	0.00	Yes

Technological optimism is moderately dependent on the subjective norm (R^2 = 0.20) (H_{IV-1}), possibly due to the absence of other factors. However, this value is not insignificant, considering a single variable explains it. Moreover, subjective norms significantly affect technological optimism (0.45). The above suggests that if students live in an environment with a positive opinion about the use of technology, they will perceive new technologies as tools that facilitate their education.

Therefore, if higher education institutions highlight the virtues of using technology in the educational process, they could create a favorable opinion among students about the benefits of incorporating these technologies.

Subjective norms and technological optimism significantly impact technological innovation (R^2 = 0.50) (H_{IV-2} and H_{IV-3}). The direct effect of subjective norms on technological innovation is 0.23, while the direct influence of technological optimism is 0.57. Additionally, technological optimism plays a statistically significant complementary mediating role between subjective norms and technological innovation.

The indirect impact of subjective norms on technological innovation through technological optimism is 0.26 (0.45*0.57). The above indicates that much of the effects of subjective norms on technological innovation are explained by technological optimism. That means a student's pioneer status in using technology is associated with a positive perception of the technology's utility. Furthermore, the perception within the academic circles of students influences their willingness to use it. The attitude toward use is moderately dependent (R^2 = 0.23) on technological optimism and innovation (H_{IV-4} and H_{IV-5}) due to the absence of variables not included in the analysis, such as perceived ease of use and perceived usefulness. Nevertheless, these personal characteristics (technological optimism and innovation) would moderately explain the students' attitude toward use.

The direct effect of technological optimism on attitude toward use is 0.33, while the direct impact of technological innovation is 0.19. The above is consistent with previous studies in other areas, which indicate that attitude toward use is influenced by technological optimism (Kros et al., 2011; Theotokis et al., 2008) and technological innovation (Al-Ajam & Md Nor, 2015; Kros et al., 2011; J. C. Lin & Chang, 2011).

Moreover, there is a statistically significant complementary mediation of technological innovation between technological optimism and attitude toward use. The indirect effect is 0.11 (0.57*0.19), indicating that only part of the impact of technological optimism on attitude toward use can be explained by mediation with technological innovation. Students need to be pioneers in the use of technologies to have a positive attitude toward adopting technologies; they must perceive these technologies as applicable. Additionally, their perceptions of these technologies in their academic circles can influence their attitude toward using them.

Finally, the model shows that behavioral intention to use strongly depends on attitude toward use (R^2 = 0.68) ($H_{IV\text{-}6}$), indicating that a student with a positive attitude toward the use of technology would intend to use it, which ultimately indicates the effective use of technology in the classroom. The above is consistent with previous augmented reality studies in other areas, showing that the intention to use is powerfully explained by the attitude toward use (Arvanitis et al., 2011; Chung et al., 2015; Mao et al., 2017; Pantano et al., 2017; Wang et al., 2016; Wojciechowski & Cellary, 2013).

4.4 Technological Acceptance of an Interactive Augmented Reality Application on Resistive Circuits for Engineering Students

The results obtained for the model evaluated in a face-to-face format (P.V) are shown in Table 5 and Figure 16 (dashed arrows indicate non-significant paths). Eight out of the ten hypotheses of the model were accepted.

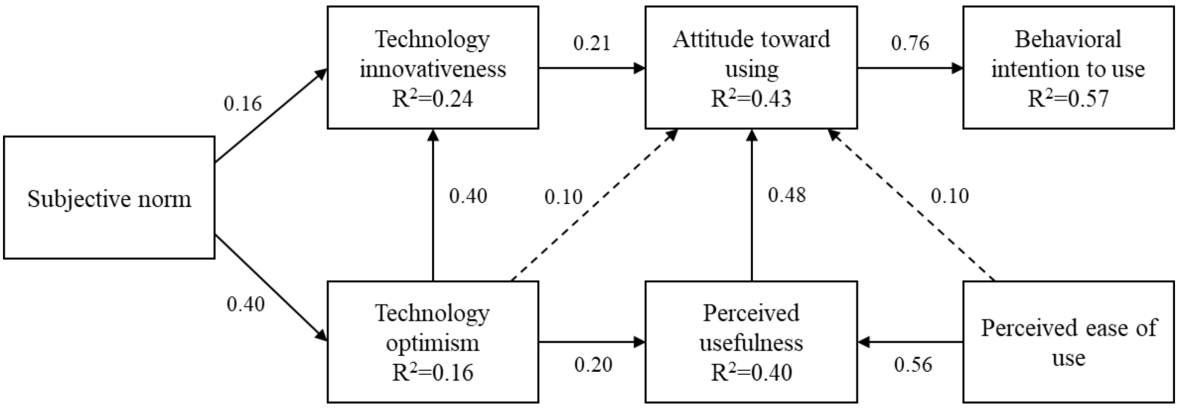

Figure 16: Research model resulting from the face-to-face evaluation.

Students' technological optimism depends on a small range of subjective norms (R^2 = 0.16) ($H_{V\text{-}1}$), suggesting that other factors better explain this element.

Technological innovation moderately depends on subjective norms and technological optimism (R^2 = 0.24) ($H_{V\text{-}2}$ and $H_{V\text{-}3}$). Technological optimism has a statistically significant complementary mediation between subjective norms and technological innovation. The direct effect of subjective norm on technological innovation is 0.16, while the indirect effect due to technological optimism is 0.16 (0.40*0.40). The above implies that technological optimism explains half of the subjective norms' impact on technological innovation. These findings are consistent with those obtained in the online evaluation.

Table 5: Results of the structural model of the face-to-face evaluation.

Hypothesis	**Path**	**p-value**	**Supported**
H_{V-1}: Subjective norm → Technology optimism	0.40	0.00	Sí
H_{V-2}: Subjective norm → Technology innovativeness	0.16	0.02	Sí
H_{V-3}: Technology optimism → Technology innovativeness	0.40	0.00	Sí
H_{V-4}: Technology optimism → Perceived usefulness	0.20	0.01	Sí
H_{V-5}: Technology optimism → Attitude toward using	0.10	0.14	No
H_{V-6}: Technology innovativeness → Attitude toward using	0.21	0.00	Sí
H_{V-7}: Perceived ease of use → Perceived usefulness	0.56	0.00	Sí
H_{V-8}: Perceived ease of use → Attitude toward using	0.10	0.14	No
H_{V-9}: Perceived usefulness → Attitude toward using	0.48	0.00	Sí
H_{V-10}: Attitude toward using → Behavioral intention to use	0.76	0.00	Sí

Perceived usefulness depends on technological optimism and perceived ease of use ($R^2 = 0.40$) (H_{V-4} and H_{V-7}). However, perceived ease of use (0.56) has a more significant impact than technological optimism (0.20), indicating that students associate an application's perceived ease of use as a strength for achieving more meaningful learning.

Attitude towards using depends on perceived usefulness and technological innovation ($R^2 = 0.43$) (H_{V-6} and H_{V-9}). Perceived usefulness (0.48) has a more significant impact than technological innovation (0.21), implying that students must clearly understand the application's utility for their studies and be willing to use it. However, technological optimism and perceived ease of use do not significantly impact attitudes towards using (H_{V-5} and H_{V-8}).

Technological optimism indirectly affects attitude towards using, caused by the moderation of technological innovation (0.400.21 = 0.08) and perceived usefulness (0.200.48 = 0.10), though both effects are insignificant.

Although perceived ease of use does not have a statistically significant effect on attitude towards using, perceived usefulness completely mediates the effect (0.56*0.48 = 0.27), meaning the application must be easy to use and useful for students in enhancing their academic performance.

Finally, the results show that the intention to use strongly depends on the attitude towards using (R^2 = 0.57) ($H_{V\text{-}10}$). The above demonstrates the critical role of a positive attitude towards the application in predicting students' intention to use it, ultimately indicating effective use of the technology in the educational setting.

4.5 Theoretical Implications

This study holds significant theoretical implications across several dimensions. Initially, the systematic review (P.I) identifies strengths and weaknesses of augmented reality technology in engineering education, pinpointing areas requiring further research and providing suggestions to researchers and application developers to enhance the effectiveness of existing methodologies.

This research underscores the need for more augmented reality applications to support the advanced skills demanded by Industry 4.0. These applications allow for the customization of exercises and their integration into centralized learning management systems to provide real-time information on student performance.

Additionally, the findings indicate that the large-scale virtualization of educational activities, such as virtual labs, holds great potential but poses educational challenges that require suitable pedagogical models. Thus, education and new technologies must be coordinated, necessitating reviewing and updating existing pedagogical models.

Another significant finding is the need for studies evaluating usability in augmented reality applications using standard approaches like SUS or ISO 9241-11. That highlights the need for research to establish standards for usability evaluation in augmented reality applications, which could have significant implications for theories of usability and user interface design.

Furthermore, the results of this study suggest that designers should consider incorporating functional features of perceptual association with the embedding of virtual objects to achieve virtual elements that interact more naturally with the environment. This finding could have important implications for theories of perception and cognition, highlighting the importance of the natural integration of virtual elements into the environment for an optimal user experience.

Regarding the empirical part of the research, two models have been proposed and validated to determine the role of optimism and technological innovation in accepting augmented reality technology and the influence of their direct environment on subjective norms.

The first empirical study (P.IV) analyzes the direct influence of these factors on attitude towards using and intention to use by engineering students. Due to the nature of the constructs analyzed and the need to compare them with the next phase, the data collection for this study was conducted online.

The second empirical study (P.V) proposed an extended TAM model to explore factors that may influence the intention to use an augmented reality application, incorporating perceived ease of use and perceived usefulness this time. Due to the nature of these last two constructs, data collection was conducted face-to-face.

Many studies have investigated the technological adoption of augmented reality. However, only some have considered the educational field, specifically engineering. Moreover, few studies have emphasized student characteristics such as technological optimism and innovation, which is particularly important because students are now digital natives. Subjective norms also become relevant to determine if they influence the evaluated characteristics of students and, eventually, the adoption of this technology. Since these factors are independent of the evaluated technology, the results can have significant implications for adopting other technologies.

Thus, the two models presented incorporate factors not studied in this context. The results of this thesis provide additional insight into the acceptance of augmented reality technology, identifying external factors specific to users and the technology. In this case, elements of the student's academic environment (teachers, classmates, family, educational institution directors, and media) can affect their disposition or beliefs about technologies, impacting their acceptance of a particular technology.

Therefore, these findings help us understand university engineering students' motivations and foundations for adopting augmented reality technology in the academic environment. Finally, in the case of the second empirical study (P.V), the results show that the TAM remains valid and predictive when evaluated in an educational context. However, a study using an application with poor design (e.g., less interactivity, aesthetics) might reach different conclusions.

4.6 Practical Implications

Firstly, the systematic review study (P.I) can benefit educators, developers, and researchers by improving augmented reality applications and their educational use in various ways. Educators interested in augmented reality can learn about different aspects of the applications, which can be helpful in decision-making, from their educational uses to technical issues, such as evaluating their impact on students.

Secondly, an augmented reality application for analyzing resistive circuits (P.II) was developed. This application can be used in theoretical classes for academics to teach concepts and behaviors of electrical circuits. It can also be used in laboratories, where students can practice learned concepts. This application resulted in a high attitude toward use and intention to use by students (P.III).

Regarding the proposed acceptance models (P.IV and P.V), the findings demonstrate that personal aspects (the belief that technologies, in general, are facilitators of various tasks and being inclined to be a pioneer in using new technologies) and environmental aspects (the importance that students give to the opinions of their academic environment, as previously explained) influence the willingness to use the application. That implies that higher education institutions can influence their students to adopt new technologies and convince them that their use will help improve their academic performance. The above could be achieved by disseminating encouraging results due to the inclusion of this technology in education.

Concerning the extended TAM model (P.V), the perceived ease of use of the application influences students' perceptions of its usefulness. Therefore, this aspect should be considered when developing applications in this area. However, students' willingness to use this technology depends on how many believe they can improve their academic performance through its use, not how easy they think the application is. That is consistent with other findings that used an application in science education (Arvanitis et al., 2011) or chemistry education (Wojciechowski & Cellary, 2013). However, these findings differ from those of other areas, such as tourism (Chung et al., 2015; Lee et al., 2017), where the attitude towards using is influenced by perceived ease of use rather than perceived usefulness. The above makes sense because when a person uses an application for studying, they expect it to impact academic outcomes positively. Conversely, when that person uses an application in a more leisurely setting, other factors motivate them, such as how easy the application is to use.

Chapter 5: Conclusions and Future Work

Augmented reality technology has not been intensively used in most engineering areas; therefore, its full potential has yet to be fully exploited. Educators interested in this technology, armed with the results provided in the systematic review (P.I), can make informed decisions when considering various aspects of the applications, from their educational uses to technical issues. There is a need for more augmented reality applications with more advanced features to encourage adoption by instructors. Developers and researchers must build applications with more sophisticated features to exploit this technology's potential fully.

The first proposed acceptance model (P.IV) helps explain the role of technological optimism and innovation in accepting augmented reality technology among engineering students. The results suggest that subjective norms positively affect optimism and technological innovation. Higher education institutions should raise awareness about the benefits of technological tools in learning to create technologically friendly environments and promote a technologically optimistic attitude. Attitude towards using can be influenced by optimism and technological innovation, and the success of implementing this technology in engineering education should consider previously unaddressed areas, such as members' attitudes towards new technologies and institutional influence on these attitudes.

A proposed extended version of TAM aims to identify the factors that explain the acceptance of augmented reality technology in engineering education (P.V). The findings suggest that the academic environment can influence students' beliefs about using this technology, increasing their willingness to use it.

Moreover, studies demonstrating how augmented reality enhances academic performance should be disseminated among educational communities. Research into variables that explain academics' intention to use it is recommended, addressing its impact on academic performance in the future. Also, this technology's relevant features, such as interactivity levels and the application's stability, should be considered to analyze their influence on acceptance.

Successful implementation of augmented reality technology in engineering education should consider areas that have yet to be addressed, such as members' attitudes towards new technologies and institutional influence on these attitudes. Using a beneficial technology may increase students' optimism towards this technology in an educational context. It should also consider how the involvement of technologically innovative students influences their peers.

Educational institutions are training digital natives, and augmented reality applications allow institutions to be more efficient in the educational process. Future engineers are expected to be familiar with this and other technologies to meet the challenges of Industry 4.0.

Future research might explore the factors influencing technology adoption among academics and consider the relevant characteristics of the technology (e.g., levels of interactivity or stability of the application) to analyze their influence on acceptance.

As a limitation, this research was conducted in the context of a developing country. In the future, the results of this study could be compared with those of other countries in broader contexts.

In summary, the adoption of augmented reality technology in engineering education is still in process, and more research and development are needed to leverage its potential.

Publications

Publication I

Álvarez-Marín, A., and Velázquez-Iturbide, J.Á. (2021). Augmented reality and engineering education: A systematic review. In IEEE Transactions on Learning Technologies, 14(6), 817-831. doi: 10.1109/TLT.2022.3144356. JCR 2021: 4,43 - Education & Educational Research (Q1); SJR 2021: 1,29 - Computer Science Applications (Q1).

Augmented Reality and Engineering Education: A Systematic Review

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***Abstract*—Augmented reality (AR) for learning is a relevant topic that has recently received considerable attention. However, the current literature lacks a survey of AR-based educational approaches and experiences in the specific field of engineering studies. Five research questions were addressed: RQ1) engineering studies where AR is used; RQ2) types of educational activities where AR is used; RQ3) evaluation of its impact on students and instructors; RQ4) relevant characteristics of AR apps; and RQ5) their degree of interactivity. Regarding RQ1, it is concluded that AR has been mainly used in technical drawing, electronics, and construction. Concerning RQ2, AR apps have assisted in lectures, exercise classes, and laboratories. However, the preferred educational activity varies for each discipline. Regarding RQ3, it has been found that AR apps have been evaluated with respect to students' or instructors' perceptions and students' academic performance. In general, the perceptions are positive, but students criticize some technical elements. Moreover, academic performance is increased in most studies. Finally, regarding RQ4 and RQ5, AR apps do not achieve the highest levels of functional characteristics and have low degrees of interactivity. The systematic review indicates that there is plenty of room for the future use of AR in engineering studies, but each engineering area must identify adequate educational purposes. It is also recommended to assess apps through objective measures, more structured constructs, and validated scales. Finally, higher functional characteristics and interactivity should be encouraged to exploit the full potential of AR.**

***Index Terms*—Augmented reality (AR), engineering education, learning technologies, systematic review.**

I. Introduction

In the recent past, emerging technologies have offered new opportunities to enhance education. Specifically, the use of computers in the classroom can improve students' experiences and increase their academic achievements. One of such technologies is augmented reality (AR) [1], where virtual and real objects are integrated in real time, often in a 3-D format. AR systems have the following features: to combine real and virtual objects in a real environment, run interactively and in real time, and geometrically align virtual and real objects in the real world [2]. AR applications (apps) can show virtual objects by using a marker that acts as a spatial reference [3]. Typically, AR apps are offered as mobile apps, although they may also rely on alternative wearable devices, such as head-mounted displays (HMDs), Oculus Rift, or HTC Vive, which provide a wider field of view and lower latency. In addition, current HMD devices can be combined with other tracker systems, such as eye-tracking systems, or motion and orientation sensors [4]. Augmentation is not limited to the sense of sight, but it can be provided for other senses, such as hearing or touch. Finally, some AR apps allow for the removal of real objects from the perceived environment [5].

AR apps have been increasingly used in the last decade. Therefore, a growing number of experiences and user experiments in different areas have been reported, including education [6]. Until now, systematic reviews on AR use in education have been conducted both in general [7]–[11] and specific fields, most notably in medicine (in particular, in the training of surgical procedures [12]–[16]). Systematic reviews are also available on the use of AR in industrial maintenance operations [2] and the usability of AR apps [6].

Five systematic AR reviews can be found in broader educational areas. The first study [7] investigates certain factors, such as the uses, advantages, limitations, effectiveness, challenges, and characteristics of AR in educational environments. The primary purpose of AR has been to explain a topic of interest, thus providing additional information. It has been effective in enhancing students' academic performance, motivation, commitment, and positive attitudes. The study also identifies some limitations of the technology, including difficulties in keeping overlaid information, paying too much attention to virtual information, and the consideration of AR as an intrusive technology.

The second study aims to analyze the use and advantages of AR technologies in educational environments [8]. The most frequently reported advantage of AR is the promotion of improvements in learning achievement. Some of the challenges highlighted thereof include AR usability and frequent technical problems.

In science, technology, engineering, and mathematics (STEM), the third study seeks to determine the characteristics of educational AR apps, their associated instructional processes, and observed learning outcomes [9]. This study concludes that AR apps should contain features intended to acquire the necessary competencies of STEM disciplines and

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provide metacognitive scaffolding and experimental support for inquiry-based learning activities.

The fourth study is a systematic review of the evaluation of AR tools for education [10]. Most of the results are positive. However, most studies lack instructor interaction and the use of multiple metrics to evaluate educational gains.

The fifth study addresses AR in primary and secondary education through game-based learning [11]. This study concludes that this type of technology can influence students' acquisition of skills, transfer knowledge, increase their interest in subjects, and enhance their digital skills.

The five studies suggest the continued observation of the effects of AR apps on knowledge construction. They also recommend exploring the learning processes present in different instructional settings and with various student populations.

In general, on the one hand, AR in education comprises exploration apps (e.g., augmented books) and games [9]. In the latter aspect, game-based learning has rapidly gained momentum by enabling new teaching approaches in primary and secondary education [11].

On the other hand, engineering addresses the design and construction of artificial artifacts. Understanding such artifacts is not an easy task, as they may have complex 3-D structures with nonvisible properties. AR has the potential to assist in learning the structure and behavior of such artifacts. Therefore, AR can be considered as a promising technology for engineering education [17].

Furthermore, AR is an alternative to face-to-face engineering education, especially by using this technology outside the classroom, thereby helping students learn at home or in distance education settings. In addition, AR is less expensive and has fewer occupational risks [17]. Thus, universities could benefit from the economies of scale effect by implementing these apps instead of traditional laboratories, since each student could access a virtual laboratory using a tablet or smartphone. Evidently, it would allow laboratory activities to be carried out in situations of confinement or restrictions, such as the COVID-19 pandemic, and if the university implemented laboratories with tablets, the investment could be more profitable as they could be reused for different subjects and apps.

Incorporating AR technology in engineering education can also favor future engineers' capabilities to incorporate into Industry 4.0. This type of industry is characterized by increasingly digitized and optimized operations that are integrated into networks under the concept of industrial AR (IAR) [18]. Notably, IAR is one of the key technologies pointed out by the Industry 4.0 paradigm to improve industrial processes and maximize worker efficiency [19]. This technology has mainly been applied industrially in manual assembly, maintenance, operations, process monitoring, process simulation, and training. It has mainly been implemented in the following industries: automotive, mechanical, electronics/automation, aerospace, and general industrial [20]. Therefore, incorporating this technology into engineering education could not only affect academic performance in the short term but also provide engineering students with skills in the long term to successfully enter the labor market of an increasingly digitized industry.

Hence, the purpose of this study is to conduct a systematic review of the use of AR technology in education engineering. To the best of our knowledge, no similar studies have been conducted. The systematic reviews cited above provide useful information about the use of AR in general educational settings. However, they fail in guiding the actual use of AR in engineering studies and identifying gaps that provide opportunities for future research. Thus, this study seeks to contribute to understanding the state of the art in the use of AR in engineering studies, including strengths and weaknesses, to identify areas requiring further research investigations and propose recommendations to researchers and app designers to improve the effectiveness of the current approaches.

The rest of this article is organized as follows. Section II presents the methodology followed by a review. Section III presents a structured presentation of the results. Finally, the article includes a summary of the findings reported, suggestions for future lines of research, and identification of implications for different stakeholders.

II. Methodology

This section describes the process followed in the systematic revision in detail. The methodology proposed by Kitchenham is adapted and used [21].

A. *Research Questions*

The following five research questions are raised regarding AR in engineering education.

RQ 1) In which engineering studies has AR been applied?
RQ 2) In what types of educational activities in engineering education have AR apps been used?
RQ 3) How have AR apps been assessed in engineering education?
RQ 4) What are the main characteristics of the AR apps used in engineering education?
RQ 5) What is the degree of interactivity of the AR apps used in engineering education?

B. *Documentation Sources*

To ensure that the relevant literature was found, four online research databases, representative of engineering education, were used: 1) Web of Science; 2) Scopus; 3) ACM Digital Library; and 4) IEEE Xplore Digital Library. A key factor for selecting these databases was their comprehensive support for conference proceedings [22].

C. *Search Items*

The following query string was searched: "engineering education" AND "augmented reality." The occurrence was required in either the title, summary, or keywords of each publication. The final search was conducted in September 2019.

TABLE I
INCLUSION AND EXCLUSION CRITERIA

Inclusion Criteria	Exclusion Criteria
(a) Any year of publication. (b) Journal article or conference paper. (c) Reporting empirical research. (d) Used in engineering education. (e) AR is the leading technological component.	(a) Citing the term "augmented reality" but dealing with "virtual reality." (b) Used for training (e.g., professional learning). (c) Emphasizing app design or development as opposed to educational use or evaluation.

TABLE II
SELECTION PROCESS

Selection Stage	# of publications
1. Result of string search in the databases	732
2. Removal of duplicate articles	583
3. Removal of articles with unavailable full texts	523
4. Application of inclusion and exclusion criteria	56
5. Removal of articles with the same authors, AR applications and studies	52

D. Selection of Studies

A set of inclusion and exclusion criteria was adopted by adapting the criteria (see Table I) used in some of the above-mentioned reviews [8], [9].

From the initial search, 732 publications were found. They were analyzed to discard duplicates, resulting in 583 unique publications. After removing publications that were unavailable in the full text, 523 remained.

Subsequently, the inclusion and exclusion criteria were applied. Articles that either cited the term AR but only addressed virtual reality, dealt with apps used for training rather than higher education, or emphasized the app's design, as opposed to its educational use, were not considered. Consequently, 56 publications remained.

Finally, four cases were found in which the authors and the study were the same. These duplicates were discarded; therefore, the final analysis focused on 52 publications. The selection process is summarized in Table II.

Of the 52 publications selected, 34 were published as conference papers while 18 were published in journals. The conferences with the highest number of selected papers are the Frontiers in Education Conference (9) and the International Conference on Advanced Learning Technologies (5). The journal with the highest number of selected articles is Computer Applications in Engineering Education, with three articles. Spain has the highest number of contributing studies (21), followed by the USA (7) and Portugal (4).

E. Methodology of Analysis

Any deficiency in the analysis procedure can reduce the validity or integrity of the results [23]. Therefore, the selected articles were qualitatively analyzed, considering the relationship between content and context [24], [25]. The analysis and classification process aimed at answering the five research questions involved several iterations. The process was stopped when a consensus was reached between the authors.

The primary source of disagreement between the authors was dissatisfaction with the resulting categories. Therefore, we present the final choice of categories used to answer each research question. For RQ1 (regarding areas of knowledge), RQ2 (regarding educational activities), and RQ5 (regarding interaction features), categorization was relatively straightforward from the studies analyzed.

For RQ3 (regarding the evaluation of AR impact), two relevant issues were identified. The first issue was the identification of the educational criteria assessed in the publications. The second issue ensued from the finding that most studies evaluated the subjective perception of students or instructors regarding AR. Here, the analysis was continued to determine the variables measured in such a study.

We analyzed the studies without predefined categories [26] through several iterations. The identification or definition of the measured variables was based on their descriptions in the studies surveyed. Once the variables were identified, their correspondence to each of the studies was analyzed. In the case of academic performance, a case-by-case analysis of the results was conducted.

For RQ4 (regarding characteristics of AR apps), a search was conducted for relevant classifications that could inspire the analysis. Two informative classifications were identified. The first classification identifies the enabling technologies used in AR [27], proposing the following dimensions: media representation, computing devices, interaction devices (e.g., user input), display, and tracking technology (e.g., tracking system). The second classification analyzes the functional characteristics of apps [28], proposing the following types: documented reality, documented virtuality, augmented understanding, augmented visibility, perceptual association, and behavioral association.

III. RESULTS

An analysis of the 52 publications resulted in the identification of 42 AR apps. The 42 AR apps can be found in [29]–[70]. The results obtained for the five research questions are as follows.

A. RQ1: In Which Engineering Studies Has AR Been Applied?

Ten engineering areas of knowledge with AR-based educational experience were identified in the papers of the study. More than 54% of the cases corresponded to technical drawing or electronics (see Table III). A short description of the application of this technology in each area of knowledge is provided ahead.

1) Technical Drawing: Experiences in this field are held in exercise classes, where geometric figures are shown in 3-D. Students are assisted in visualizing 3-D models and drawing orthographic or isometric views [34]. Some apps include video playback for a better understanding of the subject [38] and visualization of cuts in 3-D figures for a better comprehension of their structure [32]. The instructor's role is limited to either giving general explanations at the beginning of the class about

TABLE III
AREAS OF KNOWLEDGE

Area	# of apps	References
Technical drawing	12	[29]–[40]
Electronics	11	[41]–[51]
Construction	7	[52]–[58]
Manufacturing	3	[59]–[61]
Electromagnetism	3	[62]–[64]
Assembling	2	[65], [66]
Robotics	1	[67]
Production	1	[68]
Nuclear reactor	1	[69]
Topography	1	[70]

Note: $N = 42$.

the development of the activity [30], [31] or acting as a tutor in solving exercises with increasing levels of difficulty [33].

2) Electronics: There is a large variety of experience, all of which are carried out in laboratories. Most experiences involve interacting with augmented representations of real electronic boards. Using markers, it is possible to physically visualize not only the electronic components placed on the board but also the additional components. In some cases, it is possible to simulate the behavior of an electronic board augmented with switches [41], [42], [47] or determine the underlying wiring of an electronic component by selecting it with a pen pointer [43]. In other cases, repairing a board can be guided by an analysis of its parts and subsequent guidance through the subsequent steps [44].

There are also experiences with handcrafted electrical circuits. The most straightforward approach allows for the interpretation of standard electric symbols as markers, showing their corresponding components in 3-D and giving an explanatory note about each type of component [45]. A more advanced feature consists of including switches to analyze the behavior resulting from enabling or disabling them [49]. Finally, electric circuits can be set up, and their functioning can be observed through markers that represent different electronic components [45], [46], [49].

Some apps support the analysis of electronic equipment, in which the electrical and electronic components are identified. Information is provided about the equipment, such as monitoring data, display of inner structure, technical design of circuits, and instructions [48], [50].

In electronics, the instructor typically plays the role of a guide in the laboratory, either by enabling cooperation and peer learning or providing an infrastructure to conduct simulations in the laboratory [42], [44], [47], [49].

3) Construction: All experiences in this field are held in the classroom. AR apps allow for the projection of scaled models of buildings while making available complementary information, such as notes, images, and videos [56]. They also facilitate the identification of different parts of interest in a building [53], recognizing real structures and projecting an AR image on them with adjacent buildings [54] or teaching structural analysis [58]. Another study does not show buildings but construction machines in 3-D to demonstrate their characteristics and functions. It also allows several users to interact simultaneously by independently placing construction machines using markers [52]. The instructor's role is to explain and discuss the concepts covered.

TABLE IV
EDUCATIONAL ACTIVITIES

Educational Activity	# of apps	References
Lab classes	20	[41]–[51], [59]–[61], [63], [65]–[69]
Exercise classes	14	[29]–[40], [62], [70]
Lectures	8	[52]–[58], [64]

Note: $N = 42$.

4) Manufacturing: Three apps are developed to guide students enrolled in mechanical engineering courses in the handling of machinery [59]–[61].

5) Electromagnetism: There are three electromagnetism experiences. One is held in the classroom, where the magnetic fields generated by the elements are guided by mutually interacting markers [64]. The other is intended for exercise classes, where a representation of an electromagnetic field is displayed in 3-D, and it assists in solving given problems [62]. The last experience is held in a laboratory class, where the interaction of electromagnetic signals created by anthems is explained and practiced [63].

6) Assembling: Two cases are reported in laboratory classes, where information and instructions are provided to assist in solving a manually operated assembly exercise. The instructor's role is to provide guidelines for the proposed task [65], [66].

7) Other Areas: Four additional engineering fields are found, each with a single experience. Three experiences involve laboratory classes: 1) robotics [67]; 2) production line [68]; and 3) nuclear reactor [69]. Another paper reports on exercise classes wherein students practice with level curves in topography [70].

B. RQ2: In What Types of Educational Activities in Engineering Education Have AR Apps Been Used?

This research question has been partially answered in the previous section, where educational uses are identified to understand the purpose of using AR in each engineering field. Reported educational activities involving AR technology can be grouped into three categories: 1) laboratory; 2) exercise classes; and 3) lectures (see Table IV).

Most experiences are undertaken in laboratories, where students have to practice the knowledge acquired in the classroom under the instructor's guidance. In electronics, this technology is used most frequently in the laboratory, with students interacting with electrical circuits. There are also laboratory experiences in assembling, robotics, production, manufacturing, nuclear reactors, and electromagnetism.

The second type of activity whereby this technology is used is in exercise classes, though less frequently. Students rely on 3-D visual representations to better understand and address the problems to be solved. These experiences are mainly found in technical drawing, but there are also cases of their application in topography and electromagnetism.

The third type of teaching activity is lectures, whereby instructors explain concepts and methods. The main area of knowledge where this type of activity is used is construction.

TABLE V
ASSESSED CRITERIA

Criterion	# of studies	References
Students' perception	34	[29], [31], [33], [35], [37], [40]–[42], [45]–[47], [50], [51], [53]–[56], [58], [59], [62], [63], [65], [66], [70]–[80]
Students' academic performance	17	[30], [33], [35]–[38], [40], [41], [47], [55]–[58], [66], [70], [71], [77]
Instructors' perception	4	[30], [47], [74], [76]

Note: $N = 38$.

Buildings and their elements are displayed in 3-D, giving complementary information in different formats.

C. RQ3: How Have AR Apps Been Assessed in Engineering Education?

Notably, 38 out of the 52 publications include some form of assessment. The studies analyzed in this review address three evaluation criteria: 1) instructors' perception; 2) students' perception; and 3) academic performance (see Table V).

The criterion that is most frequently assessed is students' subjective perception. The goal is to determine whether AR is considered useful, pleasant, or easy to use by students. It also seeks to inquire about their motivation, satisfaction with use, acceptance, or positive opinion on AR as an effective way to acquire knowledge.

The second most frequently evaluated criterion is the technology's impact on students' performance. These studies aim to determine whether AR offers a useful tool to assist students in achieving the intended learning outcomes of their respective courses.

Finally, instructor perception is evaluated to understand their opinions about AR effectiveness as a complementary tool in courses, its use, and educational opportunities.

Studies regarding student or instructor perceptions are analyzed to identify the specific variables that are measured for this broad criterion. Eleven variables are identified and presented below in an alphabetical order.

Aesthetics represents beauty, which depends on certain issues, such as design, fonts, color, or photographs. It has been suggested that aesthetics and a beautiful interface design may determine if users decide on using a specific technology [81], in addition to obtaining enjoyment by interacting with it [82].

Facilitating conditions are external constraints that restrict the use of technology [82]. An example is whether an app is available offline after being downloaded to a mobile device or the cloud [83].

Information quality is defined as the relevance and attractiveness of information, and it is a crucial issue when an AR app delivers information [83].

Interaction is defined as the quality of the modalities supported and the degree of interaction with the objects represented [30].

Motivation represents a negative or positive feeling toward the use of technology. In the positive case, users will be more susceptible to using the technology again in the future [82].

TABLE VI
VARIABLES MEASURED REGARDING STUDENTS' PERCEPTION

Variable Measured	# of studies	References
Perceived usefulness	23	[29], [33], [35], [37], [40], [41], [46], [47], [51], [53], [54], [56], [58], [59], [63], [65], [66], [70], [72], [73], [75], [76], [78],
Satisfaction	16	[29], [33], [35], [37], [45], [50], [56], [58], [59], [70]–[72], [74], [77]–[79]
Usability	15	[31], [33], [42], [45], [47], [54], [55], [59], [66], [70], [71], [73], [75]–[77]
Motivation	14	[29], [33], [35], [40], [42], [47], [50], [51], [63], [72], [74]–[76], [80]
System quality	8	[31], [33], [42], [47], [54], [59], [70], [78]
Facilitating conditions	6	[41], [47], [70], [73], [75], [76]
Interaction	6	[33], [47], [46], [51], [54], [76]
Aesthetics	6	[35], [37], [58], [59], [72], [76]
Information quality	5	[31], [42], [54], [59], [70]
Perceived enjoyment	2	[46], [58]
Technology acceptance	1	[62]

Note: $N = 34$.

Perceived enjoyment is the extent to which using a technology is regarded as pleasant on its own [84], [85].

Perceived usefulness can be characterized as how a person thinks a specific technology will contribute to improving task performance [86], [87], such as a shorter time necessary to perform a task or activity, or higher precision [88].

Satisfaction is defined as the user's degree of pleasure while using the system [59].

System quality comprises different system features, such as support for several languages, precision, interaction operations, user interface, and app functions [83].

Technology acceptance is defined as the user's intention for a system, including whether the user accepts or rejects the underlying technology and how the features of the system influence the user's acceptance [89].

Usability is defined as the degree to which a person believes that a specific technology can be used effortlessly [88].

In the case of perception studies involving students, 11 variables are used in 34 studies (see Table VI). Only one study uses an elaborated construct, namely, technology acceptance [62] while the other studies gather simple data in perception surveys.

The most cited studies correspond to the field of electronics. The first study involves students of mechanical engineering [45]. The students indicate that they feel comfortable with the learning process and consider the app pleasant, easy to use, and useful. They find that the app is suitable for both theoretical and practical content. In the second most cited study [76], the students highlight the technical level, graphical interface, usability, and interactivity of the app. They also indicate that they disagree that theoretical concepts should be learned only by studying, without the need for practical work. In this sense, the app helps to assimilate theoretical and practical concepts. In the third most-cited study, interviews are conducted to determine students' opinions about using the app [41]. They

TABLE VII
VARIABLES MEASURED REGARDING INSTRUCTORS' PERCEPTION

Variable Evaluated	# of studies	References
Perceived usefulness	4	[30], [47], [74], [76]
Motivation	4	[30], [47], [74], [76]
Usability	3	[30], [47], [76]
Facilitating conditions	2	[47], [76]
Interaction	2	[47], [76]
Information quality	1	[30]
Aesthetics	1	[76]
Satisfaction	1	[74]
System quality	1	[47]

Note: $N = 4$.

TABLE VIII
METHODOLOGIES USED TO EVALUATE IMPACT IN STUDENTS' ACADEMIC PERFORMANCE

Methodology	# of studies	References
Experimental group vs control group, pretest, and posttest	11	[33], [36], [38], [40], [41], [55]–[58], [71], [77]
Experimental group vs control group, only posttest	3	[35], [37], [66]
Comparison with past years	2	[30], [70]
Comparison in different educational settings	1	[47]

Note: $N = 17$.

declare that the app allows them to perform laboratory experiments in less time. However, the students place too much trust in the benefits of using this app, resulting in less effort to thoroughly understand the concepts and in less time spent studying.

In general, AR presents positive opinions and achieves good acceptance among students [59]. The results show that this technology creates an engaging and attractive environment, which results in more active student participation [46]. Therefore, there is an increase in student interest and motivation [29], [53], [63] as well as in enjoyment [65]. Moreover, this technology is considered useful [45], [54]. This can lead to improved results obtained in tests [72] and is a valuable method for self-directed learning and self-evaluation [31]. Some students think that:

> *"I can get more knowledge and it can help me learn well"; "I believe it makes learning become more interesting as I am feeling very excited to see this AR myself," or "The system can be used to provide assistance in my study in the near future. So it could be very helpful" [59].*

Regarding usability, only three standardized means are used: 1) system usability scale (SUS) [45]; 2) Nielsen's attributes of usability [54]; and 3) the ISO 9241-11 standard [55]. In general, the usability aspects are duly considered. For example, in a study conducted by Martín-Gutiérrez *et al.* [45] using the SUS, the score obtained is approximately 80%. This score is considered good, as usability is deemed acceptable for values higher than 55%.

As for negative perceptions, some criticisms are made about the educational and technical aspects. Regarding the educational process, some students think that it is not easy to simultaneously follow an instructor's explanation and use an app [72], as well as study new concepts in an app without the instructors' support [47], [62], [76]. Therefore, students believe that they must have a solid theoretical base to complement their learning using the app. Some students also believe that this technology does not favor teamwork [73] because apps are generally utilized individually. However, these criticisms are due to the specific uses of AR apps. Conversely, other studies adopt a collaborative approach to AR [52], [56], thereby resulting in students' opinions favorable to teamwork (e.g., "*We can share and solve problems together*" [46]). Regarding the technical aspects related to usability, students report stability problems, flickering, and lag on the screen when manipulating virtual models [31], [54], [70].

In the case of perception studies involving instructors, only four studies are found. All the variables, except two, are used, namely, perceived enjoyment and technology acceptance (see Table VII). All the studies used simple perception surveys as the measurement instruments.

Similar to students, instructors' perceptions are positive about the use and possibilities of this technology. It could be useful toward improving the understanding of situations that require the visualization of elements in 3-D. Some instructors' opinions are:

> *"It can be used as a very good teaching–learning system"; "The system is excellent and efficient. However, if follow-up is given, the system can improve to an optimal approximation" [46]; "Students will be more focused and enjoy their learning process"; "It is really interesting and engaging. Nowadays, students are more technologically savvy, and they will be interested in this type of thing. This makes learning more fun" [59].*

The two most cited studies are conducted in an electronics laboratory. In the first one, the academics' opinions agree with the students, thus highlighting the technical level, graphical interface, usability, and interactivity of the app. However, there are differences in how instructions should be scheduled. Academics believe that theoretical concepts can be learned only through lectures and studies and that the app would not be as efficient to learn concepts. On the contrary, the students believe that theoretical concepts should be approached in a more practical way for their understanding and that the app could assist in this purpose. These results are confirmed by the second most cited article (by the same authors [47]), in which another experience with the app is reported.

The use of AR is also evaluated in 17 studies with respect to its impact on students' academic performances. The following methodologies are used (see Table VIII): Comparing an experimental group with a control group, using pretest and posttest, a single test at the end of the experiment, comparing grades obtained in the current academic year with grades obtained in past years, and comparing performance in different educational settings, such as physical, virtual reality, and AR laboratories.

TABLE IX
PERFORMANCE MEASURES

Method	# of studies	References
Spatial skills acquisition	10	[30], [33], [35]–[38], [40], [70], [71], [77]
Knowledge acquisition	4	[55]–[58]
Laboratory skills acquisition	2	[41], [47]
Assembly skills acquisition	1	[66]

Note: $N = 17$.

TABLE X
MEDIA REPRESENTATION

Media Representation	# of apps	References
3D elements	31	[29]–[40], [46], [49]–[55], [57], [59], [61]–[65], [67]–[70]
Texts or symbols	4	[42]–[44], [66]
Animation	3	[45], [58], [60]
Videos	2	[41], [56]
Images	2	[47], [48]

Note: $N = 42$.

Regarding the performance of students trained with AR apps, tests are used to measure skill acquisition (including spatial skills, laboratory skills, and assembly skills) and knowledge acquisition (see Table IX).

Of the 17 studies that consider academic achievement, only two report no evidence of improvement in student performance. The first of these cases correspond to a remote AR laboratory, where students have no direct relationship with AR objects [47]. The abovementioned shows that this technology could have a more significant effect on activities where students directly visualize and interact with learning elements, thus achieving substantial learning.

The second case, which does not show any influence on performance, is a structural analysis app, the only one that addresses this subject [58]. In this case, it seems that the visualization of elements in 3-D does not influence the acquisition of knowledge.

All the studies that assess spatial skills yield a positive impact on the development of spatial abilities by facilitating a faster understanding of spatial problems and complex relationships, helping in the teaching process, positively impacting learning outcomes, and improving academic performance. This is consistent with the perception that AR apps allow for a faster understanding of spatial problems and complex relationships.

Of the four studies that evaluate knowledge acquisition, three correspond to apps related to construction and execution issues in technical projects. According to the questionnaire's answers, the performances of the students using the AR app improve in all cases. The fourth study corresponds to a structural analysis app [58]. This study shows no significant differences in performance between the experimental and control groups. This is likely because, although the app allows for the visualization of the forces applied in a structure and their effects, it does not give students the added value produced by solving the corresponding formulas.

The two studies related to electronic laboratory skills present mixed results. In the first study, the experimental and control groups are compared using laboratory experiments. With the help of a smartphone, students in the experimental group are facilitated via videos, graphs, and links to supplementary materials to assist them. The study concludes, after a 5-week training, that students who use the AR app achieve a statistically significant improvement in their performance [41]. In the second study, an AR laboratory to work remotely is implemented, and three groups of students are formed in the electronics laboratory (traditional classes, virtual laboratory, and remote laboratory with AR). The students perform two laboratory experiments. In the first one, students design a digital sequential control system using a development board, in which the virtual laboratory group performs better. In the second experiment, the students develop a control system for a robot to avoid obstacles. They use monitor-based stereo glasses to interact with AR elements superimposed on a real scenario, assisted by their computer mouse. The best results are obtained by both the group that conducts the traditional laboratory and the one that uses the AR app [47].

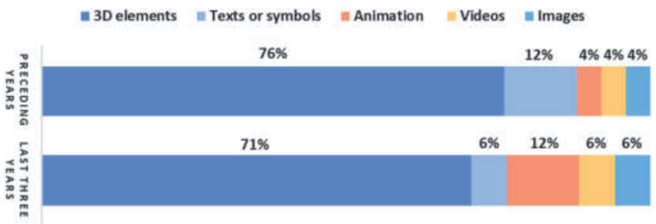

Fig. 1. Media representation—last three years versus preceding years.

The most cited study [41] is used in electronics laboratories (electrolysis of water, Ohm's law, Wheatstone bridge, Kirchhoff's law, and three-phase transformer connections). The second most cited study [47] compares three groups of students in the electronics laboratory (traditional classes, virtual laboratory, and remote laboratory with AR). Both studies have been summarized in the previous paragraph. The third most-cited study [66] uses an AR app in assembly tasks. The results show that students who use the AR app significantly reduce the assembly time and the number of steps used.

D. RQ4: What Were the Main Characteristics of the AR Apps in Engineering Education?

For this research question, we again focus on the 42 apps identified. In the literature, we find two adequate classifications of AR app characteristics: 1) enabling technologies [27]; and 2) functional features [28].

Five enabling technologies are distinguished by Wang *et al.* [27]: 1) media representation; 2) computing devices; 3) user input; 4) display; and 5) tracking system. Below, we include their definitions, as well as their use in the publications reviewed.

1) Media Representation: This represents the form in which information is displayed. It can be text, symbols, images, videos, elements in 3-D, or animation. Most publications use elements in 3-D for graphic representation, four use texts or symbols, three use animations, two use videos, and two other apps use images (see Table X).

TABLE XI
COMPUTING DEVICES

Computing Device	# of apps	References
Desktop/ laptop	18	[29], [30], [35], [36], [38], [42]–[44], [46], [47], [49], [60], [61], [64], [66], [68]–[70]
Tablet/ smartphone	18	[31]–[34], [39]–[41], [48], [50], [51], [53]–[57], [62], [63], [67]
Wearable devices	6	[37], [45], [52], [58], [59], [65]

Note: $N = 42$.

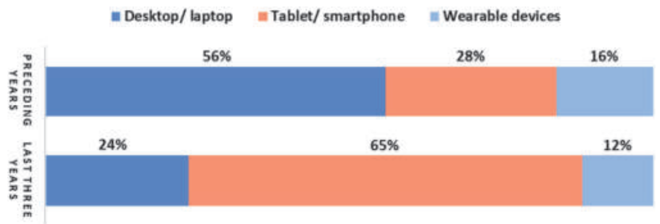

Fig. 2. Computing device—last three years versus preceding years.

TABLE XII
USER INPUT

User Input	# of apps	References
Device movement	32	[29], [30], [32]–[41], [48], [50]–[63], [65]–[67], [69], [70]
Controls	4	[41], [42], [47], [68]
Markers position	4	[45], [46], [49], [64]
Gestural entries	1	[31]
Pen pointer	1	[43]

Note: $N = 42$.

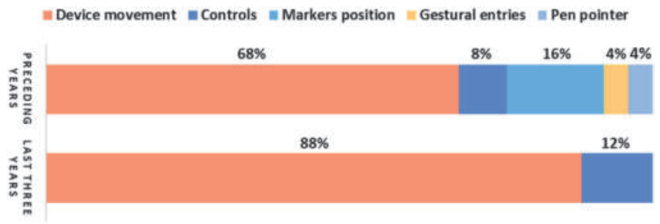

Fig. 3. User input—last three years versus preceding years.

In the last three years, compared to the preceding years, animation has been the media representation that increases the most in its use, from 4% to 12% of the total analyzed apps (see Fig. 1).

2) Computing Device: This identifies the computing device that processes the AR app. It can be a desktop computer, laptop, tablet, smartphone, or wearable device (see Table XI). In total of 18 apps are used on a desktop computer or a laptop. In many cases, the authors argue that the app is a prototype and, therefore, portable technology is not used to reduce development effort. In total of 18 apps use tablets or smartphones for their operations. Finally, six cases use wearable devices, namely, AR lenses. These lenses are used in complex apps, such as the app developed by Restivo *et al.* [52]. They conduct a collaborative learning experiment using marker-based AR, with several users simultaneously viewing and interacting with the scene. In the last three years, compared to the previous years, tablets and smartphones are the computing device category that increase the most in their use, varying from 28% to 65% of the total analyzed apps (see Fig. 2).

3) User Input: This identifies the means adopted by the user to interact with virtualized information, that is, through controls, gestural entries, or device movements (see Table XII). Thirty two of the apps use device movements (tablet, smartphone, or webcam) to interact with virtual elements. Four apps use controls, and four apps require moving the associated markers to interact. Only one app supports touch gestures in the device [31]. Another app supports interaction utilizing a pen pointer, thereby allowing 3-D spatial localization and multimodal feedback (vibrations, tactile stimulations, heat) about invisible electronic characteristics, such as electronic noise or power dissipation [43].

In the last three years, compared to the previous years, device movement has been the form of device interaction that has increased the most in use, rising from 68% to 88% of the total analyzed apps (see Fig. 3). In addition, the minority interaction modes disappear.

TABLE XIII
DISPLAY

Display	# of apps	References
Monitor-based display	35	[29]–[36], [38]–[44], [46], [48]–[51], [53]–[57], [60]–[64], [66]–[70]
HMD with monitor-based output	4	[37], [45], [52], [65]
Optical see-through HMD	2	[59], [58]
Monitor-based stereo glasses	1	[47]

Note: $N = 42$.

4) Display: This is the device used by the app for display, such as a monitor-based display (e.g., tablet, smartphone, desktop, or laptop screens), monitor-based stereo glasses, HMDs with monitor-based outputs, or optical see-through HMD outputs (see Table XIII). Thirty five apps use a monitor-based display. Four apps use an HMD with a monitor-based output. Finally, two apps use an optical see-through HMD (users can watch the virtual information provided by the system while interacting with their hands [59]), and one app uses monitor-based stereo glasses. In the last three years, new display technology has been used (optical see-through HMD), unlike HMDs with monitor-based outputs and monitor-based stereo glasses, which have been discontinued.

5) Tracking System: This technology enables the determination of the position of an object in real time. Whenever the user moves the AR device, the tracking system recalculates the new position in real time; thus, the virtual contents remain aligned with the real object. These systems include marker-based tracking (including images as markers) and markerless tracking. Among the latter, we can find natural feature tracking, model-based tracking, and simultaneous localization and mapping (SLAM). Natural feature tracking consists of finding natural features in a scene [90]. Model-based tracking uses a 3-D model to estimate the object's position. This method is commonly used for tracking 3-D objects without texture [90].

TABLE XIV
TRACKING SYSTEM

Tracking system	# of apps	References
Marker-based tracking	34	[29]–[38], [41], [42], [45]–[53], [55]–[63], [65], [68]–[70]
Natural feature tracking	5	[39], [40], [43], [44], [54]
Model-based tracking	3	[64], [66], [67]

Note: $N = 42$.

TABLE XV
FUNCTIONAL CHARACTERISTICS

Functional Characteristics	# of apps	References
Augmented visibility	29	[29]–[40], [46], [49]–[55], [57], [58], [60], [62]–[65], [69], [70]
Perceptual association with incrustation of virtual objects	6	[45], [47], [59], [61], [67], [68]
Documented reality	3	[42], [48], [66]
Documented virtuality	2	[41], [56]
Augmented understanding	2	[43], [44]

Note: $N = 42$.

Finally, SLAM provides a real-time estimation of 3-D models from the sole input [91]. The most common tracking system is marker-based tracking, but some cases of natural feature tracking and model-based tracking have also been reported. No other tracking system is used in the experiences gathered (see Table XIV).

The second classification of AR app characteristics considers functional characteristics. Hugues *et al.* [28] distinguished documented reality, documented virtuality, augmented understanding, augmented visibility, perceptual association with an overlay of virtual objects, perceptual association with the integration of virtual objects, and behavioral association with the integration of virtual objects. Note that in Table XV, only five of the seven characteristics distinguished by Hugues *et al.* are found.

The occurrences of these characteristics in the app are presented in an increasing degree of complexity.

6) Documented Reality: This is a minimal feature of the AR. Virtual entities and real images are displayed on two different panels of the screen. The information displayed is related to the reality shown, with narratives, and helps the user to understand and guide specific actions, if necessary [28]. Three apps present this characteristic (two in electronics and one in assembling). Documented reality has been used to deliver complementary information to correctly perform an activity, such as written instructions for the user.

7) Documented Virtuality: This displays real objects complemented with static information to achieve a better understanding [28]. Two apps have this feature, in electronics and construction. Video is the most often used medium to deliver complementary information. In the construction area, students focus their mobile devices on images shown in the textbook, which results in playing or displaying multimedia items (videos, sounds, and images) to explain or reinforce the technical concepts given by the instructor. In addition, support is provided to enable collaborative work with classmates and discuss the information given [56].

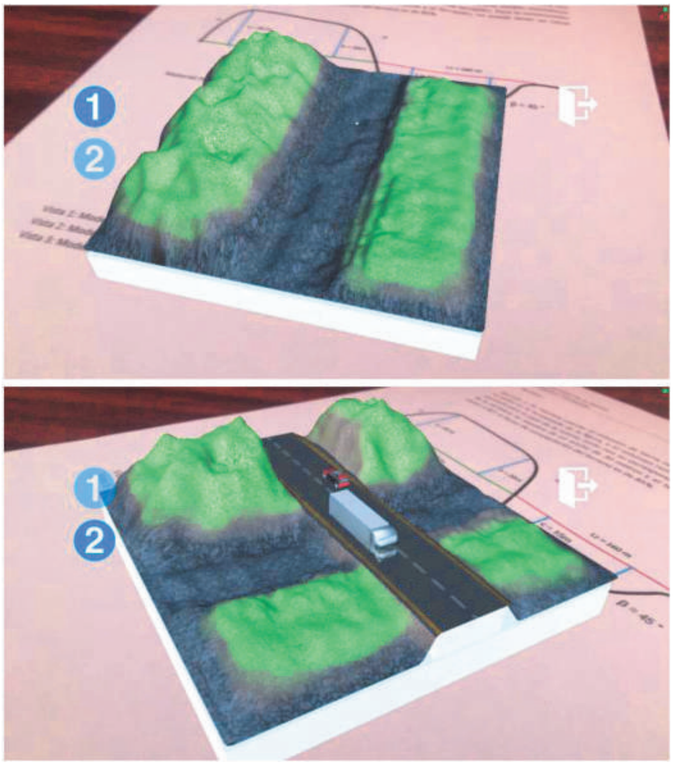

Fig. 4. Augmented visibility's example. Two AR views are shown of a loading and transportation exercise in engineering. The objective is to visualize a small mountain before and after the construction of a road. That can help the student calculate the volume of earth required to build the road with an embankment in the gully and determine the earth's volume removed required for the road's passage, together with its corresponding embankment.

8) Augmented Understanding: This implies embedding complementary information into real images to enhance their knowledge [28]. Two apps use this characteristic, both in electronics. In one study, the students have to identify the different pieces of electronic boards [44]; in the other, the students have to follow instructions in a real environment [43].

9) Augmented Visibility: This displays virtual objects that geometrically match the contours of real objects to improve their understanding [28] (see Fig. 4). This is the most common characteristic of the apps found in this study. A total of 29 apps present augmented visibility, including all the apps used in technical drawing to visualize mechanical or electronic pieces in 3-D [29], [31], [34], [46], [49]. This type of experience can be found in other subjects as well, such as the areas of construction of buildings [55], types of machinery in 3-D [52], electromagnetism [62], or level curves in 3-D [70].

10) Perceptual Association With an Overlay of Virtual Objects: This feature incorporates virtual objects into a real scenario, visually superimposing them over reality [28]. Six apps use this characteristic. Two are in electronics, where virtual objects are embedded into an electronic board [45], [47]. Two are in manufacturing, where elements are incorporated into the types of machinery of productive processes [59], [61]. Finally, one is in robotics, adding an arm on an artifact for its operation [67], and another is in production,

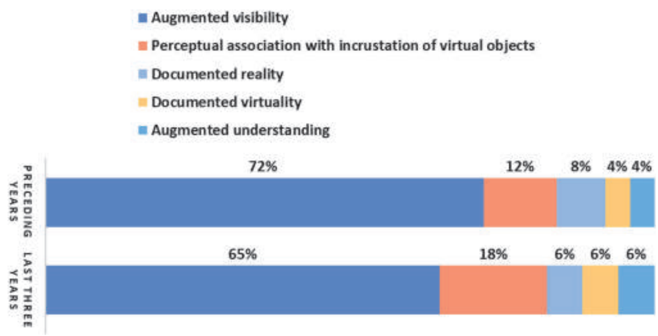

Fig. 5. Functional characteristics—last three years versus preceding years.

where elements are added on a production line [68]. In the last three years, compared to the previous years, perceptual association with an overlay of virtual objects has been the functional characteristic that increases the most in its use, varying from 12% to 18% of the total number of analyzed apps (see Fig. 5).

E. RQ5: What Is the Degree of Interactivity of the AR Apps in Engineering Education?

In the publications analyzed, only 10 apps are found to explicitly support some degree of interactivity (see Table XVI). Electronics is the area where more interactive apps are reported, totaling six. Electronic boards can be manipulated through switches in AR to check their performance [42], [47], [49], or electrical circuits can be assembled, and their correct behavior is tested [46], [51]. Among these studies, one of the pioneers of interactive AR apps is the most cited [49]. The second most-cited study corresponds to an app that shows electromagnetic fields in 3-D interacting with each other through the movement of markers [64]. In this case, the app shows the resulting magnetic field during contact. This case shows a 3-D figure to understand it and visually explains its interaction and results.

The third most-cited study corresponds to an app in the construction area [58]. This app allows for the visualization of 3-D models to illustrate how structures behave under different loading conditions. Students can interactively change the load and observe the reaction resulting from this change with instant feedback.

Interactive apps have also been developed in three additional areas. In robotics, the arm of a machine can be manipulated using a 3-D image of the same arm on the monitor [67]. In the production area, the process in a production line can be manipulated using AR elements, resulting in manipulations of a programmable logic controller [68]. Finally, an interaction is found in a study of nuclear reactors, where their cores and the manipulation of extraction rods are simulated. The representation and movement of both the rod and the core are shown in AR [69].

In general, the interactions that are achieved with AR apps are limited. In electronics, the area with the most interactive apps, the majority only show operating states when handling switches. In only a few cases, the user can interact with the elements of electrical circuits to check their correctness without performing further computations (e.g., voltage or current).

TABLE XVI
TYPES OF INTERACTIONS OF APPS

Type of Interaction	# of apps	References
Interaction	5	[42], [47], [49], [67], [68]
System simulation	3	[58], [64], [69]
Assembling	2	[46], [51]

Note: $N = 10$.

IV. DISCUSSION

In this section, the systematic review results are summarized, and the main threats to validity are identified. The findings obtained for the research questions are successively presented, as well as a discussion of them and the suggested opportunities vis-à-vis future research.

A. RQ1: In Which Engineering Studies Has AR Been Applied?

This technology has been applied more frequently to technical drawing and electronics. In technical drawing, as well as construction and topography, 3-D visualizations of elements are displayed to increase understanding. In electronics, more diversity has been found based on modeling electronic components with some level of interaction. The use of this technology has hardly been expanded to other areas of engineering education.

The use of AR is heterogeneous in different engineering education areas. An open question is whether this situation comes from the different adequacy of AR to the educational needs of different areas or just by lack of interest in those areas. The absence of AR in "virtual engineering" areas, such as computing or telecommunications, can be an argument for the first hypothesis. In effect, disciplines whose natures are virtual do not need AR because they already use a myriad of virtual resources and materials in digital devices (e.g., software visualization for programming or algorithms [92]). A deeper study would elucidate this issue.

In the literature reviewed, AR is used to explain concepts and basic skills. Although the technology may potentially support the development of advanced skills that in the future will be demanded in Industry 4.0, this is currently not the case. Therefore, there is a niche for more AR apps in this regard. Sectors that could benefit from IAR include automotive, mechanical, automation, and aerospace [20].

B. RQ2: In What Types of Educational Activities in Engineering Education Have AR Apps Been Used?

The types of educational activities in which AR apps have been used are markedly dependent on the subject. Typically, AR apps have been used in electronics laboratories to interact with electrical circuits. In contrast, they have mostly been used in technical drawing exercise classes, where the 3-D interactive visualization features of AR are exploited to solve problems. Finally, the use of AR in lectures is most common in construction, mainly to deliver complementary information, such as notes, images, and videos.

Even in areas where this technology is used, it is in the minority. More meditation on educational scenarios and exercises adequate to each area is necessary, and more AR apps should be designed, implemented, and evaluated. Thus, for technical drawing, AR could be more than just a tool for visualizing 3-D elements. For electronics, the types of activities that can be performed in the laboratory with the help of apps can be expanded. In construction, AR can provide more than just supporting information. In other areas, these trails have not been blazed.

Efforts should be made to integrate the design of AR apps with active learning methods. For instance, one of the most successful active learning methodologies is collaborative learning [93], especially in laboratory activities. Currently, some students (and perhaps instructors) mistakenly believe that AR discourages teamwork and encourages individual learning. In fact, it is so when app usage is limited to delivering descriptive information, visualization of 3-D elements, and simple tasks. However, some successful experiences [46] suggest that AR can successfully support collaborative learning.

Moreover, apps should allow for the customization of exercises by academics and even students, so that more demanding exercises can be stated and higher levels of cognitive development can be achieved by students.

Another suggestion for future work is the integration of AR apps into centralized learning management systems to provide real-time feedback on student performance and track student activities and individualized difficulties.

Large-scale virtualization of activities, especially virtual laboratories, has not been fully exploited. Notwithstanding the potential benefits claimed in the introduction, it also brings about educational challenges. Academics must plan their participation as a guide in this type of activity, which is different from traditional instruction. Student-centered pedagogical models and flipped classrooms can be useful in the development of such educational processes.

C. RQ3: How Have AR Apps Been Assessed in Engineering Education?

Another concern of the research has been whether the impact of this technology has been evaluated in realistic educational situations. The assessment criteria documented in the publications are students' and instructors' perceptions and students' performance. Perceptions are subjectively scored using surveys, while academic performance is mostly evaluated using controlled experiments with pretest and posttest designs.

In general, it seems that AR increases students' interest and motivation and promotes active participation in learning situations. Academics also have positive opinions regarding the aspects consulted.

Students find apps useful to improve their academic performance and undertake autonomous work. However, they consider it necessary to have a theory explained prior to using the app to autonomously reinforce such knowledge. This opinion contrasts with academics' beliefs that it would be useful to use it at an early stage by students to learn new concepts.

A negative aspect indicated by students is the technical problems (e.g., stability, flickering, and lag in the apps), which may be due to the novelty of the underlying technology or insufficiently elaborated prototypes.

Some variables can be studied using more elaborated instruments than subjective surveys. A representative example is a usability, where the lack of studies with standard approaches, such as the SUS or ISO 9241-11, does not provide adequate information about the most common pitfalls in the user interfaces of AR apps. Several technologies, such as eye-tracking services, could also be used to analyze user interaction with the app, obtain feedback, and support designers and programmers in improving this type of app. Another example is motivation, wherein validated questionnaires exist based on psychological theories, such as self-determination theory.

Similarly, more structured variables can provide deeper information on different aspects of the educational process. One representative example is technological acceptance, of which only one study has been documented [62]. Research on acceptance shows the factors that influence the adoption of this technology in educational settings.

Perception has been evaluated much more often for students than for instructors. Conducting more studies on instructors is recommended, as they are key agents in the adoption of educational technologies.

Regarding the impact on academic performance, the most often measured criterion is spatial skills. In general, AR has shown a positive impact on academic performance. In particular, all the studies show an improvement in the development of spatial abilities. However, the number of studies on other skills and/or concepts is small. More controlled evaluations are necessary to obtain more representative and generalizable results. AR should also be evaluated in additional subjects and educational approaches.

D. RQ4: What Are the Main Characteristics of the AR Apps Used in Engineering Education?

The apps' characteristics are analyzed with respect to two different classifications. The first classification identifies five enabling technologies. Most apps use 3-D representations, with a growing tendency to use animation. Most apps are found to run on desktops or laptops. However, their use in mobile devices is growing. Most AR apps simultaneously use monitor-based displays, marker-based tracking, and movement of devices as input means.

Concerning the second classification, functional characteristics, the most frequently used attribute is augmented visibility, using 3-D elements to support spatial skills training.

Future AR apps could be improved by enhancing their sophistication based on several characteristics. Thus, designers should study the incorporation of the functional features of perceptual association with the integration of virtual objects to obtain virtual elements that interact more naturally with the environment. It would also be desirable to further explore markerless tracking systems, thus achieving a more fluid interaction with the environment without the need for markers.

E. RQ5: What Is the Degree of Interactivity of AR Apps Used in Engineering Education?

Only about one-quarter of the studies' apps have some degree of interactivity. Furthermore, their degree of interactivity is relatively low, and customization of the learning experience is minimal. Therefore, more efforts should be devoted to developing apps that allow for higher levels of interactivity. The resulting educational activities would be richer, and students could play an active role.

F. Relation With Previous Reviews

Although no systematic reviews on educational AR have been found for engineering, the results can be compared with previous studies in other educational areas (education [7], [8], [10], [11], and science education [9]). An interesting finding is that the most recurrent educational settings found in this review are laboratory activities and exercise classes, as opposed to other studies, where the main focus is on explaining specific topics. This may be due to the nature of the subjects and educational level. In engineering subjects, such as electronics and technical drawing, skills training is performed more efficiently. This differs from other areas and educational levels wherein AR mainly serves to deliver knowledge [9]. Regarding the assessment of AR use, most studies assess students with respect to either their perception of technology or the measurement of improvement in their academic performance. For the former criterion, most engineering studies that address perception use surveys, while in other areas, it is common to use other qualitative methods, such as case studies [8], [10].

All studies agree that technology generally leads to improved learning achievement and promotes better academic performance. They also agree that they improve certain aspects, such as learning motivation, student engagement, and positive attitudes, among others [7], [8]. This is because of the interaction and graphical content used. However, they also warn that their positive impact may be due to the novelty of the technology. Furthermore, these are mainly cross-sectional studies. They also concur with the incorporation of longitudinal studies to determine if the results are maintained over time.

Regarding the technical characteristics of the apps used, marker-based AR technology is the most commonly used, as well as their use in desktop computers and mobile devices [7], [8], [11]. Desktop computers have been used, especially as educational establishments have computer laboratories. Mobile devices are used because a large number of students have them more frequently.

The studies also agree on the lack of interactivity or customization of the apps. For example, Bacca *et al.* [7] find that only 2 of 32 studies report personalized processes. Generally, the apps show predetermined situations, with a low degree of customization for the construction of new educational scenarios.

G. Threats to Validity

Three main threats to validity can be identified. First, a systematic review is created by searching four databases that are highly relevant in engineering education [22], [94]. However, conferences or journals that are not recorded in such databases may contain additional interesting articles on AR apps and engineering education. Second, the number of papers that address some issues is minimal (most notably, instructors' perceptions, Table VII). Therefore, these issues have hardly been researched, and the conclusions obtained may not be representative of reality. Third, the research can be expanded with additional strings.

Regardless of these limitations, the study is conducted using a well-defined process, finding a high number of publications, and the analysis is highly informative.

V. Conclusion

This article presents a systematic review of the state of the AR technology applied to engineering education. It has been found that AR has not been intensively used in most engineering areas; thus, its potential has not yet been fully exploited. The findings reported can be useful to educators, developers, and researchers to improve AR apps and their educational use in different ways. Educators interested in AR can be aware of different aspects of apps, which can be useful in decision-making, from their educational uses to more technical issues or ways and variables to evaluate their impact on students. More AR apps with more advanced features are necessary to foster instructors' adoption. Accordingly, developers and researchers should make an effort to construct apps with more sophisticated characteristics to fully exploit the potential of AR. Researchers should also persist in using more objective measures, elaborated constructs, and validated scales in evaluations.

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Publication II

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Interactive AR App for Real-Time Analysis of Resistive Circuits

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***Abstract*— An augmented reality app for real-time analysis of direct current in resistive circuits is presented. The app allows the manipulation of circuit elements and computes the values of voltage and current intensity using the loop method and applying the Kirchhoff's voltage law. The app can be used in theoretical classes and laboratories. The contributions of this paper are twofold. First, the app has higher levels of interactivity than other apps in the same domain since it allows defining the configuration and the parameters of the circuit. Second, the app performs more complex computations than similar apps in real-time.**

***Index Terms*— Augmented reality, resistive circuits, laboratories, DC analysis.**

I. Introduction

AUGMENTED reality (AR) technology integrates virtual objects, often in three-dimensional models, with real scenarios in real-time [1]. It allows the user to observe objects in the real world while simultaneously delivering additional information, such as virtual object overlays [2] or explanatory instructions [3]. AR is increasingly used in different areas, including education [4]. The use of AR in the classroom can contribute to improving students' experiences. Its implementation in educational processes has achieved more active participation by students [5], increasing their interest and motivation to learn [6]–[8]. This technology has also been shown to increase students' academic performance due to its ability to allow a quick understanding of spatial problems and complex relationships [9]–[11].

Electronics is one of the areas where AR educational apps have been used. Most of the experiences in this area are carried out in laboratories and allow interaction with real electronic boards. Using *targets* (element or marker, which must be recognized by a device such as a *smartphone* or a *tablet*, to identify the position of a virtual object to be projected), it is possible to visualize real electronic components on the boards also additional virtual components. In some cases, it is possible to simulate the behavior of an electronic board with switches as AR elements [12]–[14] or to know the inner wiring of an electronic component by selecting it with a pen pointer [15]. In other cases, apps can guide an electronic board's repair by analyzing its components and then through step-by-step guidance [16].

Besides, there are experiences with electrical circuits designed with symbols. This more straightforward approach allows interpreting standard electrical symbols as *targets*, showing their components in three dimensions and giving an explanatory note for each of them [17]. A more advanced feature is to include switches to analyze the circuit behavior when enabled [18]. Also, electrical circuits can be configured through *targets* representing different components to allow the user to observe the resulting operation [5], [17], [18].

Some apps support electronic equipment analysis. Electrical and electronic components are identified and provide different information types, such as monitoring data, visualization of the internal structure, technical circuit design, and instructions, among others [19].

Usually, the instructor plays a guiding role in laboratory classes [20], either supporting learning as a peer-to-peer guide [21] or providing the conditions to perform simulations [13], [14], [16], [18].

We analyze the degree of interactivity in these AR apps. Aqel [22] proposes four levels to examine the degree of interactivity.

Level I: Passive. The interaction is straightforward and unidirectional. The learner is only a receiver of information, reading text on a screen, viewing graphics or illustrations, among others.

Level II: Limited interaction. Apps consider a simple two-way interaction with the student. As an example, simple questions can be incorporated for the student to answer.

Level III: Complex interaction. The student can manipulate graphical objects to analyze their behavior.

Level IV: Real-time interaction. The student can interact in a simulation where stimuli generate complex responses.

We found that only four apps had interactivity. Electronic boards can be manipulated through switches in augmented reality to see how they work [13], [14], or to assemble basic electrical circuits to analyze if they were configured

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correctly [5], [17]. However, these apps' degree of interactivity only reaches level III, leaving little room for a more flexible educational use. Consequently, it is relevant to address the development of AR apps with a higher degree of interactivity.

AR technology has a high acceptance to address it in electronics because students consider it a tricky subject [17]. Electricity concepts are challenging to understand because they cannot visualize what electricity is and how it works [5]. For example, they do not understand the current flow within the circuit or the differences between serial and parallel circuits. Consequently, making electricity visible through AR apps makes the subject more intuitive for them [18].

This paper presents an AR app designed to facilitate electrical circuits' learning, based on a higher degree of interactivity than existing apps.

An app to analyze direct current (DC) in resistive circuits was developed. A resistive circuit can include batteries, light bulbs, and resistors. The app allows the user to change the batteries' voltage values and the resistance value of the light bulbs and resistors under controlled safety conditions. Although the light bulbs are resistors, they were created to show the effect of current intensity on their luminosity. Also, the app calculates in real-time and displays the resulting current and voltage values.

With the above, students will have the chance to experiment with different circuits, combining various elements (batteries, light bulbs, and resistors), creating many configurations. They will understand different types of current behaviors while practicing with serial and parallel circuits by modifying their elements' resistance or voltage values.

It is rare for similar apps to perform this type of calculation considering the circuit conditions. These features allow academics and students to practice and experiment with a wide range of exercises. For all of the above, the proposed app reaches the maximum level of interactivity (level IV), corresponding to real-time interaction, with complex responses by the app [22]. Existing AR apps, such as the one proposed by Restivo *et al.* [18], reach level III of interactivity, corresponding to a complex interaction because they only allow placing elements in predefined positions in an electrical circuit, not performing the calculation of current intensity in real-time.

The structure of the article follows. Section II points out the theory used for the development of the app. Section III presents relevant development details and explains events related to the AR objects. Section IV a case to show the functionalities of the app. Section V its validation as an educational tool, where it shows the results of a perception survey applied to engineering students.

II. Underlying Model for Analyzing Resistive Circuits

The app solves resistive circuit analysis exercises with the loop current method [23]. The circuit mesh shown in Figure 1 will be used as an example to address the development of current and voltage calculations and show how the app works.

This method consists of the following steps.

Step 1: Although the address assigned to a loop current is arbitrary, it is assigned a clockwise current. In each loop,

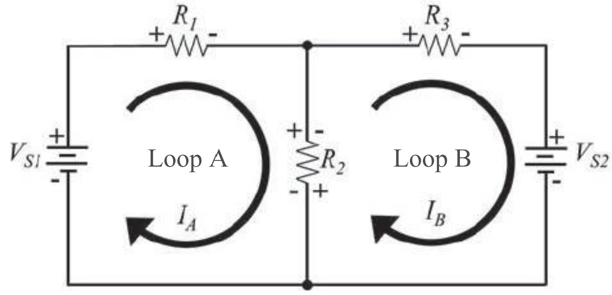

Fig. 1. Resistive circuit with loop method.

it should have only one current assigned to it to avoid redundancy. This current direction may not be real, but this does not matter in the first instance. The number of loop current assignments should be sufficient to include circulating currents through all circuit components.

Step 2: The polarities of the voltage drop in each loop are indicated according to the assigned current directions.

Step 3: Kirchhoff's voltage law is applied around each loop. When more than one current passes through a component (e.g., R_2 in Figure 1), the analysis must consider voltage drop. In this way, an equation is obtained for each loop.

Kirchhoff's voltage law applied to the two loops in Figure 1 produces the following equations:

$$R_1 I_A + R_2 (I_A - I_B) = V_{S1} \text{ for loop A} \quad (1)$$

$$R_3 I_B + R_2 (I_B - I_A) = V_{S2} \text{ for loop B} \quad (2)$$

Similar terms present in the equations are grouped and reordered in the standard way. Each unknown corresponding to the currents must have the same position in each equation, i.e., the I_A term goes first, and I_B is placed second. Equations (1) and (2) are rearranged as follows:

$$(R_1 + R_2)I_A - R_2 I_B = V_{S1} \text{ for loop A} \quad (3)$$

$$-R_2 I_A + (R_{2+} R_3)I_B = -V_{S2} \text{ for loop B} \quad (4)$$

With equations (3) and (4), the following system of equations structure is obtained:

$$a_{1,1}x_1 + a_{1,2}x_2 = b_1 \quad (5)$$

$$a_{2,1}x_1 + a_{2,2}x_2 = b_2 \quad (6)$$

Step 4. The resulting equations (5) and (6) for the loop currents are solved using determinants. The coefficients $a_{1,1}$, $a_{1,2}$, $a_{2,1}$, $a_{2,2}$, V_{S1}, and V_{S2}, are replaced in equations (7), (8), and (9) to obtain the values of I_A, I_B, and I_C.

$$I_A = \frac{\begin{vmatrix} b_1 & a_{1,2} \\ b_2 & a_{2,2} \end{vmatrix}}{\begin{vmatrix} a_{1,1} & a_{1,2} \\ a_{2,1} & a_{2,2} \end{vmatrix}} \quad (7)$$

$$I_B = \frac{\begin{vmatrix} a_{1,1} & b_1 \\ a_{2,1} & b_2 \end{vmatrix}}{\begin{vmatrix} a_{1,1} & a_{1,2} \\ a_{2,1} & a_{2,2} \end{vmatrix}} \quad (8)$$

$$I_C = I_A - I_B \quad (9)$$

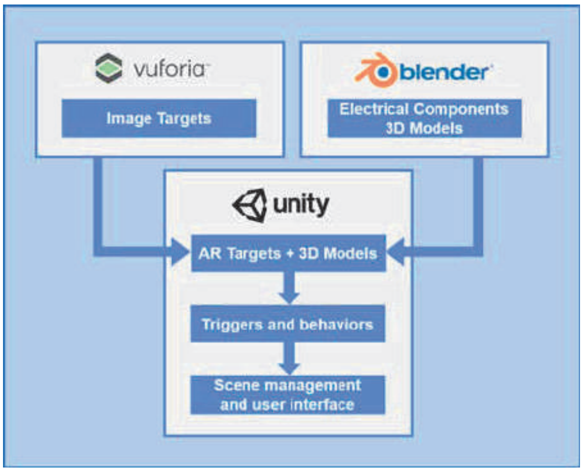

Fig. 2. App's architecture.

III. App Design and Implementation

In this section, development details are presented. The above is relevant for programming and explains events related to AR objects. The app, called "*INGAR DC Analysis,*" operates five different resistive circuit meshes. These circuits can be select on the start screen. One mesh corresponds to a serial circuit, while four correspond to parallel circuits, which can interact with up to four batteries, light bulbs, and resistors simultaneously.

The app architecture consists of three development environments: *Vuforia*, which recognizes and manages the targets; *Blender* for object modeling; and *Unity* as the graphics engine. The latter synchronizes the targets and the 3D models to obtain the AR objects. Besides, it is in charge of capturing trigger events (*Triggers*) and setting behaviors. It is also in charge of managing the order of scenes and the app's user interface (Figure 2).

The app development is facilitated using *prefabs* (predefined elements) obtained from the *Vuforia SDK*. The app uses an optical *tracker* in its operation. This technology allows to accurately determine the position of a virtual element in a real environment. Circuits, batteries, light bulbs, and resistors use a *QR* code as a *target* to position each associated AR object in space.

The 3D objects were created with *Blender*. A model corresponding to the resistive circuit was created, consisting of seven branches numbered 1 to 7 (Figure 3). A branch is a path between two nodes where the AR objects that will interact can be included.

The batteries have been assigned a default voltage value of 10 V. Its polarity can be changed.

The light bulbs were assigned a predetermined ohmic resistance of 10 Ω. The luminous intensity of the light bulb depends on the current intensity flowing through it.

Two types of resistors were created, a four-band and a five-band resistor. They were assigned a predetermined ohmic resistance of 10 Ω for 4-band resistors and 100 Ω for 5-band resistors.

A collider component was incorporated in each of the elements (circuit, batteries, light bulbs, and resistors). A collider component (capsule, box, sphere, or mesh) provides a volume to a digital object to detect whether physical collisions occur between elements. Each of the seven branches of the circuit was assigned a capsule collider, while batteries, light bulbs, and resistors were assigned a box collider (Figure 4).

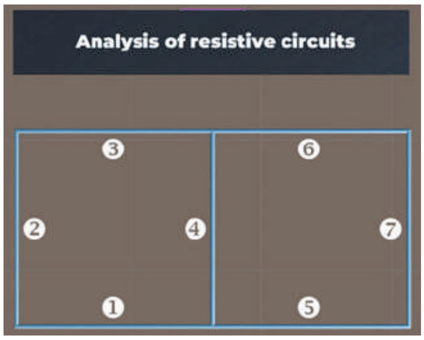

Fig. 3. Unity circuit composed of seven branches.

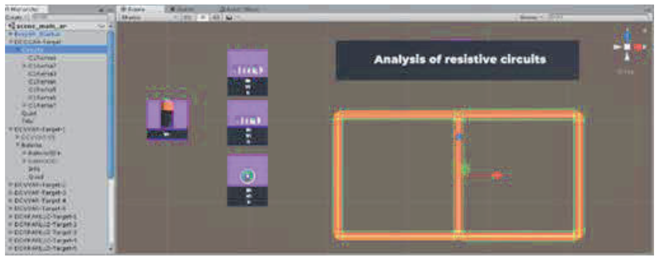

Fig. 4. AR objects with their respective colliders.

Unity's scripting system can detect when collisions occur and instantiate actions using the *OnCollisionEnter* function. However, it can also use the physics engine to detect when a collider enters another collider's space without creating a collision. A collider configured as a *Trigger* (using the "*Is Trigger*" property) does not behave like a solid object and will allow other colliders to pass through it. When a collider enters the space of another collider of type Trigger, the *OnTriggerEnter*, *OnTriggerStay*, and *OnTriggerExit* functions will be called in the object's *Trigger* scripts [24].

During the development of the app, all object colliders were configured as *Triggers*. Each of the circuit branches is assigned the label "circuit" to identify when there is an interaction with another element labeled "battery," "light bulb," or "resistor."

A *script* called "*calculator*" was created, assigned to batteries, light bulbs, and resistors, and is executed when any of these components come in contact with the "circuit."

When the AR objects contact the circuit, *OnTriggerEnter*, *OnTriggerStay*, and *OnTriggerExit* events are triggered.

The app identifies the values of the bulb and resistor type objects present in the branches using the function *GameObject.Find "(*branch number"*). GetComponent <FindComponent> (). Coef.*

Likewise, the app identifies the voltage values of the batteries utilizing the function *GameObject.Find* "*(*branch number"*). GetComponent <FindComponent> (). Cons.*

The "*calculator*" *script* solves the equations of *Kirchhoff's* voltage law utilizing equations (7), (8), and (9) using the function *m.GetDeterminant* ().

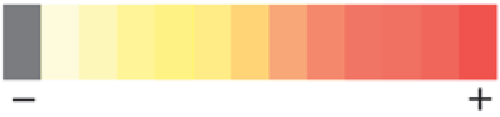

Fig. 5. Values scale of current intensity.

The app also assigns a color according to the current flowing value in each branch of the circuit. Gray indicates no current flowing through the branch, yellow corresponds to low current intensity, orange to medium current intensity, and red to high current intensity (Figure 5).

Tests of the app were performed, and two problems were evidenced.

First, the display of several AR objects was unstable. When incorporating several targets, some of the AR objects stopped displaying. The above resulted in instability in the development of the experience. At the beginning of the app design, two *trackers* were considered, the first one exclusively for the circuit and the second one for the other elements. However, the solution to this problem was to use a single *tracker*. Most mobile devices have one camera and use only one *tracker*; therefore, these mobile devices caused conflicts in target detection when working with an app that tried to access two *trackers*.

After having solved the above problem, difficulties were detected in the calculation of real-time equations. At first, each type of AR object had a single *QR* code in common as a *target*. For example, three light bulbs in a circuit used the same *QR* code. Upon detecting multiple *targets* of the same type, the app instantiated the same number of prefabricated AR object elements. When a *target* momentarily lost focus, a new AR object was generated. The above caused the default in the AR objects to be reset. That also caused duplicate values to remain in the app's calculation process, which also affected the results. The solution to these problems was to assign an individual *target* for each AR object. For example, when displaying three light bulbs in a circuit, three different targets are used.

Solving both problems allowed the app to achieve the expected levels of stability by correcting visualization and calculation of equations in real-time. However, the app has limitations inherent to the technology: small degrees of instability and flickering of the virtual objects [25]–[27].

IV. An Application Case

An exercise involving a circuit with two batteries (10 V and 5 V) and three resistors (470 Ω, 820 Ω, and 220 Ω) will be solved to illustrate how the app works. The app is required to calculate the current through each branch of the circuit. In the app, the loop currents I_A and I_B are mapped clockwise. Loop A is composed of branches 1, 2, 3, and 4, while loop B comprises branches 4, 5, 6, and 7 (Figure 6).

First, the AR objects are incorporated into the loop (Figure 7). The default values of each of the objects are configured according to the exercise.

As an example, the change in the ohmic resistance value of the resistor of branch 4 is shown. The resistor is touched on the mobile device screen, and an interface will appear where the ohmic resistance value can be changed (Figure 8). Once the resistor value has changed, it displays its new value corresponding to 220 Ω in the circuit, and its rings change color according to the international standard.

The other elements corresponding to the exercise are incorporated, configuring each of their values. The circuit identifies when the two batteries and the three resistors come into contact in the app.

The app identifies the resistors positioned in branches 1, 2, and 3. Then assigns the sum of their values to R_1 (in this case, 470). It identifies the resistors positioned in branch 4 and assigns the sum of their values to R_2 (in this case, 220). It identifies the resistors positioned in branches 5, 6, and 7 and assigns the sum of their values to R_3 (in this case, 820).

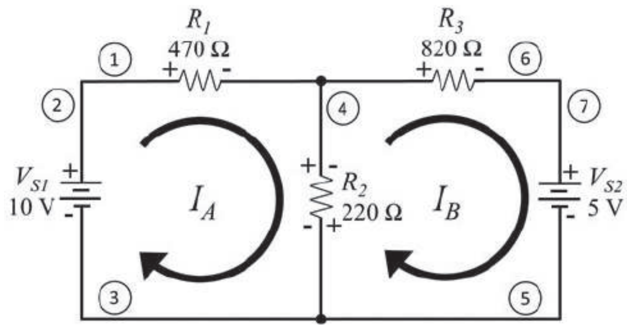

Fig. 6. Suggested exercise. Circles identify the number of each branch.

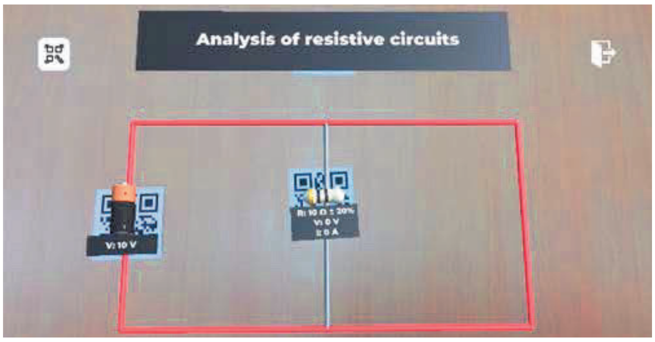

Fig. 7. Circuit with the first objects, with default values.

Fig. 8. Change of ohmic resistance value of the resistor.

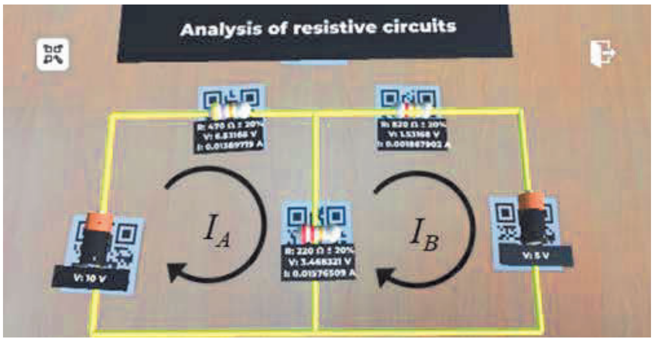

Fig. 9. Circuit of the proposed exercise, with AR objects' values resulting.

The values identified by the app are replaced in equations (3) and (4) to obtain equations (10) and (11).

$$690I_A - 220I_B = 10 \text{ for loop A} \quad (10)$$

$$-220I_A + 1040I_B = -5 \text{ for loop B} \quad (11)$$

The app constructs matrices for currents I_A and I_B, using the values obtained from equations (10) and (11).

The app calculates the matrices' determinants and obtains the values of I_1, I_2, and I_3. The resulting values are as follows: $I_1 = 13.9$ mA; $I_2 = -1.87$ mA; $I_3 = 15.8$ mA (Figure 9). The value of I2 is negative, indicating that it goes in the opposite direction of the proposed solution.

The app "*INGAR DC Analysis*" is available for download at the following link: www.ingarlabs.com/dcanalisis.

V. Validation as an Educational Tool

A. Perception Survey

We sought to measure variables that could explain students' attitudes towards the app and determine its potential use in their studies.

For this purpose, the variables *Attitude toward using* and *Intention to use* were incorporated into a survey to measure engineering students' perceptions. *Attitude towards using* refers to the user's evaluation regarding the convenience of using a given technology [28]. In contrast, the *Intention to use* is defined as the subjective probability that a person will use a system [29]. These variables were chosen, due to their presence in models proposed to predict information technology adoption behavior, [30]–[35].

A literature review was conducted to adapt the questions for the selected variables. Five questions were used for *Attitude toward using* [36] and three for *Intention to use* [37]. No questions on the respective variables were discarded from the original studies. A 5-point Likert scale was used (1-totally disagree; 2-disagree; 3-neither agree nor disagree; 4agree; 5-totally agree).

The app developed was evaluated by students of the Universidad de La Serena. They are in their third and fourth years of Engineering, and their academic programs include a subject of electromagnetism, where electrical circuits are taught. The subject consists of eight laboratory sections and is taught by four academics.

An online survey was used for data collection. In the beginning, the survey contained a three-minute video showing how the "*INGAR DC Analysis*" app works. The video shows each circuit supported by the app: one circuit with serial mesh and four circuits with parallel meshes. The video is available at youtu.be/2BEOJ2n2E3w.

TABLE I
Perception Survey Results

Variables		
Attitude towards using	Mean	SD
I think that using the app in classrooms would be positive	4.55	0.82
The app is so interesting that you want to know more about it	4.19	0.8
It makes sense to use this app to study electrical circuits	4.69	0.69
The app is a good idea	4.64	0.71
Other people should use the app	4.24	0.81
Average for Attitude towards using variable	*4.46*	*0.79*
Intention to use		
I would like to have this app if I were to study electrical circuits	4.6	0.7
I would intend to use this app to study electrical circuits	4.5	0.7
I would recommend other students to use this app to study electrical circuits	4.5	0.7
Average for Intention to use variable	*4.5*	*0.7*

At the end of the survey, a link was included where students could download the app on *Google Play* (for *Android* systems) and *APP Store* (for *IOS* systems). The app had a total of 158 downloads. Students could practice on their mobile devices outside of class, the exercises showed in the video, and others freely available.

A total of 124 students responded to the survey. Of these, 83 were male, and 41 were female. Forty students belonged to the Industrial Engineering program, 31 to Mechanical Engineering, 26 to Mining Engineering, 11 to Civil Engineering, and 16 to other engineering programs. Table I shows the average responses of the students when answering the perception survey.

B. Discussion of Results

Preliminary results establish a positive attitude towards the "*INGAR DC Analysis*" app. The variable *Attitude towards using* obtained an average of 4.46, while the *Intention to use* received a 4.5. Through these high scores, students confirm the convenience of using the app in their studies.

Within the responses, it stands out that the students find the app a good idea and that it makes sense to use it as a support tool in the learning of electrical circuits. Thus, students find incorporating this app in the learning of electrical circuits positive. They would also like to know more about how the app works and believe that other students should also use it, which may be highly recommended. The above demonstrates a positive attitude to use the app for their studies should they be able to avail of it.

Intention to use also scored high. It highlights that students would like to have this app to study electrical circuits. The above shows that there is more than a good disposition towards the tool, but there is a real willingness to use it. That is complemented by a genuine intention to recommend the use of this app to other students. This variable alone should be sufficient to predict the use of this technology [38]. Therefore, it can be inferred that there is a real intention by students to use this app for learning electrical circuits.

VI. Conclusion

INGAR DC Analysis, an AR app for DC analysis in resistive circuits, has been introduced. It allows interacting batteries, light bulbs, and resistors with a circuit. It displays in real-time current intensities and voltages in each of the elements.

The app can be used in theory classes for academics to teach electrical circuit concepts and behaviors. It can also be used in laboratory settings, where students can practice concepts learned. The app can encourage kinesthetic learning as students must move AR objects to perform the exercises.

The app has two outstanding features not found in similar ones. First, the user can customize the mesh and circuit parameters. Therefore, there is a wide range of exercises available for students to experiment and actively learn. Besides, the app solves each problem by performing non-trivial calculations in real-time.

A perception survey was conducted with students in engineering programs. The results indicate a positive attitude toward using and a high intention to use the app. The latter variable should be sufficient to predict that students will use this app to study electrical circuits.

In the future, it is proposed to measure the usability of the app [39] and conduct more complex studies to determine other variables to explain the intention to use the app. An example of the above is determining a model of acceptance of this technology through structural equations, incorporating the *Perceived Ease of Use* and *Perceived Usefulness* [30], when using this app in an academic activity under controlled conditions.

Also, variables specific to students and their relationship with technologies can be incorporated, such as their *Technological Optimism* and their tendency to *Early Adoption of Technologies* [40]. It is also proposed to determine the impact of their use on students' academic performance and determine teachers' perception of their educational value.

Finally, it is suggested to analyze this interactive tool's integration potential with a centralized learning management system, including real-time availability for the teacher. Thus, new related content could be integrated by tracking the exercises solved and the students' difficulties.

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Publication III

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Intention to use an interactive AR app for engineering education

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Abstract

Augmented reality (AR) has been incorporated into educational processes in various subjects to improve academic performance. One of these areas is the field of electronics since students often have difficulty understanding electricity. An interactive AR app on electrical circuits was developed. The app allows the manipulation of circuit elements, computes the voltage and amperage values using the loop method, and applies Kirchhoff's voltage law. This research aims to determine the intention of using the AR app by students. It also looks to determine if it is conditioned by how the survey is applied (online or face-to-face) or students' gender. The results show that the app is well evaluated on the intention of use by students. Regarding how the survey is applied, the *attitude towards using* does not present significant differences. In contrast, the students who carried out the online survey presented a higher *behavioral intention to use* than those who participated in the guided laboratory. Regarding gender, women showed a higher *attitude toward using* and *behavioral intention to use* this technology than men.

Keywords: Augmented reality; technology acceptance; engineering; education.

Index Terms: Applied computing --- Education --- Interactive learning environments.

1 Introduction

AR is a technology that has been incorporated in different areas, one of which is education, which has been shown to help improve academic performance [1]. In engineering, one of the subjects that this technology applies is electronics. Students find some concepts difficult to understand, such as electricity, since they cannot visualize how it works [2].

One of the complex elements for understanding is the behavior of current flow in an electrical circuit, and the differences between serial and parallel circuits when certain elements are incorporated (batteries, light bulbs, and resistors). Hence, making the electricity that passes through the circuits visible through an AR app makes these concepts more intuitive [3].

However, if students are not interested in using a particular technology, they would not reap the benefits of this delivery. Therefore, it is necessary to determine if students would accept this technology, in this case, as an AR app for the study of electrical circuits. The acceptance of technology seeks to explain its use and is related to the *behavioral intention to use* [4]. Likewise, studies carried out in RA have determined that the *attitude toward using* positively influences the *behavioral intention to use* [5], [6].

It is also interesting to determine if the intention to use this technology depends on whether the student was instructed to use this technology in a guided laboratory class or an independent instance where they can download the app and practice freely. The above is important because situations where people cannot meet in large numbers (for example, confinement or meeting restrictions by COVID-19), taking these measuring remotely, can be a good alternative.

Finally, it is also useful to determine if gender influences the *behavioral intention to use* this technology. That is due to the historical disparity that women present in this area of engineering education.

2 App Design

An AR app to analyze digital current (DC) in resistive circuits was designed. A resistive circuit may include batteries, light bulbs, and resistors. The app has to choose five types of circuits in serial and parallel. These circuits allow any configuration and simulate current flow when batteries, light bulbs, and resistors are incorporated.

The app allows the user to change the batteries' voltage values and the resistance of light bulbs and resistors. Furthermore, the app calculates in real-time and displays the resulting values of voltage and amperage (Figure 1).

By exhibiting a higher degree of interactivity than existing apps [2], [7], it allows students to practice and experiment with a wide range of electrical circuit configurations.

The app computes the circuit configuration results proposed by using the loop method and applying Kirchhoff's voltage law [8].

The app uses an optical tracker in its operation. Circuit, batteries, light bulbs, and resistors use a QR code as a target to position each AR figure in the space. The app was developed in *Unity 3D* using the *Vuforia SDK*. The development of the app is facilitated using prefabs. The prefabs are obtained from the *SDK*.

Three-dimensional objects were created with *Blender*. Objects corresponding to the five types of resistive circuits were developed. Batteries, resistors, and light bulbs were designed as objects in AR to interact with the resistive circuit. QR codes were used as targets.

The voltage can be assigned to the battery with a default value of 10v. The battery can change its polarity. Four band resistors and light bulbs were created with a default value of 10Ω. The light intensity of the light bulb is dependent on amperage.

A collider component was incorporated into each element, defining the object to identify if batteries, resistors, or light bulbs

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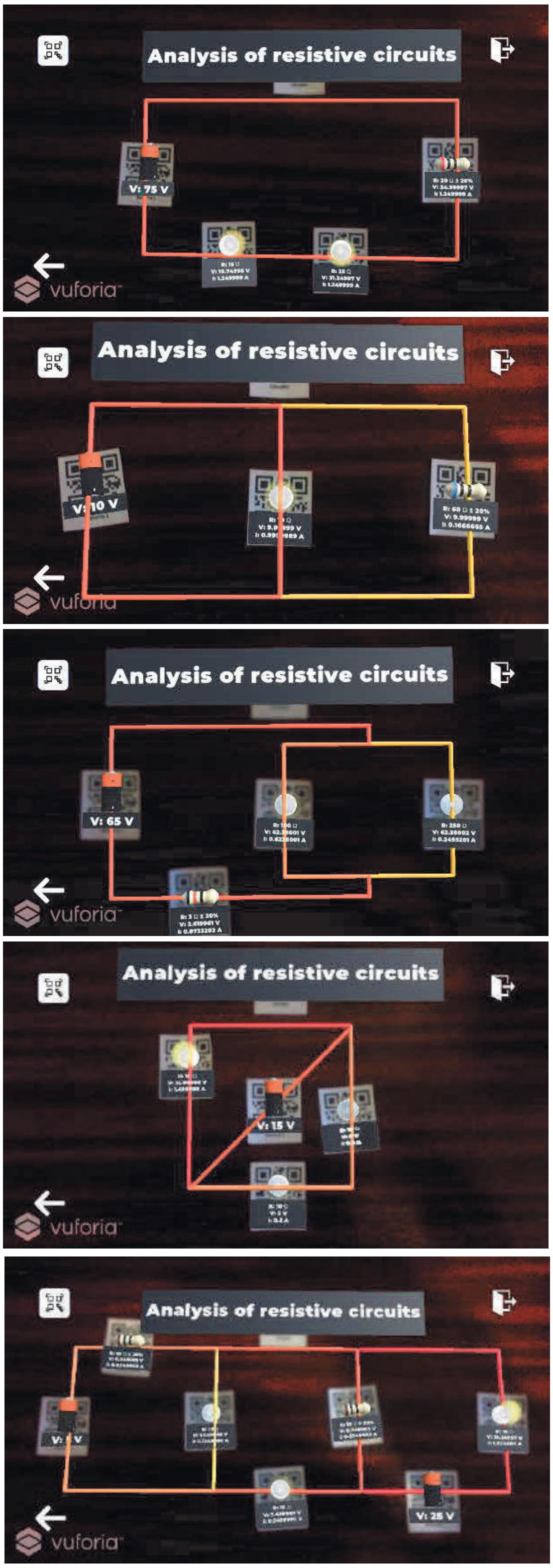

Figure 1: Interactive AR app

contact the circuit. Each branch of the circuits was established as a capsule collider, while batteries, resistors, and light bulbs were defined as box colliders.

A script called "calculator" was created, assigned to batteries, resistors, and light bulbs, and was executed when they contacted the "circuit." The "calculator" script solves Kirchhoff's voltage law equations, depending on the objects' values that interact with the circuit and assigns voltage and amperage to each one of them.

The app also assigns a color according to the amperage's value circulating in each circuit's branch. A gray branch means no amperage, yellow means low amperage; orange means medium amperage, and red means high amperage.

3 Methodology

The type of sampling used was probabilistic and for convenience in third- and fourth-year students studying engineering programs at the University de La Serena. The above is because there are subjects that teach electrical circuits within their study plans.

A measurement instrument based on the TAM model proposed by David [9] was applied. The variables *attitude toward using* (ATU) and *behavioral intention to use* (BIU) were used due to their ability to explain the attitudes that a person may have to use a given technology. *Attitude toward using* refers to the user's evaluation regarding the convenience of using a particular technology [10]. *Behavioral intention to use* is defined as the subjective probability that a person uses a system [11].

A literature review was performed to adapt the questions of the selected variables. Five items were selected for the variable *attitude towards using* and three items for the variable *behavioral intention to use* (See Table 1). No item from the original studies was ruled out. The instrument was developed considering a 5-point Likert-type scale (1-totally disagree; 2-disagree; 3-neither agree nor disagree; 4-agree; 5-totally agree).

The instrument was applied in two groups. The first group, called "Online," the students were invited to participate via e-mail, through an online survey. At the beginning of the survey, a three-minute video was shown explaining the use of the app. A link was also added where students could download the application from Google Play (for Android systems) and APP Store (for IOS systems). The students were able to use the app freely. Next, they were asked to complete the survey.

The second group, called "Laboratory," students were invited to participate in a guided laboratory class. Those who agreed to participate declared that they had not been involved in the "Online" group. The students were instructed by a teacher who explained and trained them in the app's use in an ad-hoc laboratory implemented with Tablet. They were shown a three-minute video to explain how the app works. They then used the app for approximately 30 minutes with guided exercises. These exercises aimed to understand different circuits' behavior, combining different elements (batteries, light bulbs, and resistors) and varying their voltages and resistances, as appropriate. Students were able to understand different types of current intensity behaviors while practicing with serial or parallel circuits and modifying voltages and resistances' values. Finaunderstood answer the survey.

In both groups, student participation was voluntary and was not associated with any evaluation or awarding extra points. The anonymity and strict confidentiality of the data were guaranteed.

Table 1: Studies used and questions

Variable	Item	Study	Question
Attitude toward using	ATU1	[6]	I think using the app in classes would be positive.
	ATU2		The app is so interesting that you want to learn more about it.
	ATU3		It makes sense to use the app for the study of electrical circuits.
	ATU4		The app is a good idea.
	ATU5		Other people should also use the app.
Behavioral intention to use	BIU1	[12]	I would like to have this app if I had to study electrical circuits.
	BIU2		I would intend to use this app to learn about electrical circuits.
	BIU3		I would recommend other students to use this app to study electrical circuits.

The Cronbach's alpha reliability coefficients for each of indicators were evaluated in both experiments. The STATGRAPHICS Centurion XVI 32-bit edition software was used to establish the groups' indicators' effect. An analysis of variance (ANOVA) was applied. Differences between mean values were analyzed using the least significant test difference (DMS) with a significance level of $\alpha = 0.05$ and a 95% confidence interval ($P < 0.05$). Also, the multiple range test (MRT) included in the statistical program was used to demonstrate homogeneous groups within each of the parameters.

We also analyzed whether there are differences in *behavioral intention to use* and *attitude toward using* for each gender concerning the study participants.

Table 2: Overall result

Item	Mean		SD
ATU1	4,487	±	0,742
ATU2	3,952	±	0,925
ATU3	4,649	±	0,652
ATU4	4,643	±	0,619
ATU5	4,328	±	0,739
ATU Mean	4,412	±	0,553
BIU1	4,414	±	0,771
BIU2	4,305	±	0,820
BIU3	4,359	±	0,775
BIU Mean	4,359	±	0,693

4 Results

One hundred ninety students answered the survey in the "Online" group, where 115 were men and 75 women. Seventy-five are in industrial engineering, 38 in mining engineering, 32 in mechanical engineering, 26 in civil engineering, and 17 in environmental engineering.

One hundred twenty-four students participated in the second group corresponding to the guided class. Eighty-three are men, while 41 to women. The group consisted of 40 students of industrial engineering, 31 of mechanical engineering, 26 of mining engineering, 11 of civil engineering, four of environmental engineering, and 12 of other programs.

For the 314 respondents, each item's overall results and their averages are presented in Table 2. The results for each of the "Online" and "Laboratory" groups are presented in Table 3. The findings by gender are shown in Table 4. Cronbach's alpha values are accepted for each indicator as they are higher than 0.9 [13]. The p-value of the F-test, when it is less than 0.05, indicates that there is a statistically significant difference between one group and another, with a level of 95% confidence.

Table 3: ANOVA - Groups

	"Online" Group				"Laboratory" Group				
Item	**Cronbach's Alpha**	**Mean**	**±**	**SD**	**Cronbach's Alpha**	**Mean**	**±**	**SD**	**p-value**
ATU1	0.930	4.548	±	0.820	0.918	4.447	±	0.686	0.239
ATU2	0.929	4.194	±	0.803	0.924	3.795	±	0.968	0.000
ATU3	0.922	4.685	±	0.691	0.919	4.626	±	0.628	0.433
ATU4	0.921	4.637	±	0.714	0.922	4.647	±	0.551	0.886
ATU5	0.927	4.242	±	0.810	0.917	4.384	±	0.686	0.096
ATU Mean	0.913	4.461	±	0.594	0.908	4.380	±	0.525	0.204
BIU1	0.922	4.565	±	0,678	0.912	4.316	±	0.813	0.005
BIU2	0.926	4.492	±	0.716	0.910	4.184	±	0,862	0.001
BIU3	0.920	4.500	±	0.716	0.914	4.268	±	0.801	0.010
BIU Mean	0.916	4.519	±	0.602	0.904	4.256	±	0.730	0.001

Table 4: ANOVA - Gender

Item	Female			Male			p-value
ATU Mean	4.502	±	0.462	4.360	±	0.596	0.003
BIU Mean	4.468	±	0.580	4.296	±	0.746	0.034

5 Discussion and conclusions

The overall results show that the students present a high level of *attitude towards using* and *behavioral intention to use*. The best-evaluated items were ATU3 and ATU4. Thus, students find it meaningful to use the app to study electrical circuits exercises and believe that it is good to complement their learning.

The lowest item corresponds to ATU2 related to the students' interest to know more about the app. The above could be explained because the students were shown a video about the totality of the app's functions, and they were also able to practice with it extensively.

Furthermore, this item is the only one that corresponds to the variable *attitude towards using* where the "Online" group presents a significantly higher valuation than the "Laboratory" group. That may be because the laboratory group had the support of an academic to develop guided exercises on electrical circuits. Thus, the students could solve their doubts about the app's operation in the class's progress.

Unlike the *attitude towards using*, the *behavioral intention to use* did show a significant difference. The "Online" group obtained a better evaluation of all items. That could be explained because the students in this group had the opportunity to explore one of the app's great benefits: being a tool that facilitates autonomous learning. The students were able to download and use the app from their homes without needing to be in a laboratory to exercise with electrical circuits.

The students' intention of wanting to have the app, wanting to use it for learning, and wanting to recommend it to others for study, demonstrates to students that it made sense of the way the AR app addresses the subject of electrical circuits.

Regarding gender, it was shown that women presented a higher level of *attitude towards using* and *behavioral intention to use* this technology than men. Both differences were significant. The above suggests that higher education centers should include gender in the diffusion models of these learning technologies.

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Publication IV

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The acceptance of augmented reality in engineering education: the role of technology optimism and technology innovativeness

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ABSTRACT

This study aims to determine if *technology optimism* and *technology innovativeness* can explain and predict the use of augmented reality in the scope of engineering education. An Augmented Reality app to analyze digital current (DC) in resistive circuits was developed was developed to enhance students' understanding of electricity. The app allows the manipulation of circuit elements, computes the voltage and amperage values using the loop method by applying Kirchhoff's voltage law. A model with the following variables was theoretically conceived: *subjective norms*, *technology optimism*, *technology innovativeness*, *attitude toward using* and *behavioral intention to use*. The study considered a sample of 173 engineering students and was carried out using structural equation modeling. The findings suggest that *subjective norms* have a positive effect on *technology optimism* and *technology innovativeness*. Further, *attitude toward using* was found to depend on a medium range of students' characteristics, such as *technology optimism* and *technology innovativeness*. The results suggest that the academic environment can influence a student's beliefs concerning new technologies. Understanding how the educational environment can affect students' attitudes toward the use of new technologies can help higher education institutions establish policies for their adoption to facilitate the learning process.

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Introduction

Information technology use could be highly beneficial for organizations in achieving their objectives. However, acceptance of these new technologies is necessary to realize the benefits, and the education system is no exception. New technologies can be incorporated into the teaching and learning process to improve students' performance, granting them the opportunity to be more competitive by learning more efficiently and effectively via a student-cantered way of teaching (Al-Maroof & Al-Emran, 2018). However, students' resistance to new technologies poses a challenge in the implementation. Therefore, it is necessary to understand the factors that predict and explain the acceptance of new technology by its users to suggest initiatives that will lead to successful implementation.

One such new technology is Augmented Reality (AR), which has been integrated into various disciplines (Akçayır & Akçayır, 2017; Ibáñez & Delgado-Kloos, 2018; da Silva et al., 2019), including engineering (Nesterov et al., 2017). AR integrates virtual and real objects in real-time, usually in 3D

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(Billinghurst & Duenser, 2012), allowing the user to visualize additional information such as superimposed objects (Azuma, 1997) or explicatory instructions (Feiner et al., 1993). While virtual reality technology completely envelops the user in a virtual environment, AR complements reality (Azuma et al., 2001). AR has been increasingly used in different areas, including education (Dey et al., 2018), and has been shown to improve academic achievements (Akçayir et al., 2016). It enables enriching learning experiences, facilitates learning, increases motivation, and improves focus among students (Sırakaya & Sırakaya, 2020).

Moreover, AR technology has shown great potential and has had a significant impact on higher education (Radosavljevic et al., 2020). This impact has been observed in various fields such as probabilities and mathematics (Cai et al., 2020), maintenance (Gavish et al., 2015), fashion design (Elfeky & Elbyaly, 2021), and social sciences (Toledo-Morales & Sanchez-Garcia, 2018), among other disciplines. Although many studies have investigated the use mobile technologies in education (Arici et al., 2019), some gaps have not been addressed. Particularly, there is a lack of research on augmented reality educational materials (Cabero-Almenara et al., 2019a) and their implementation in the classroom (Cabero-Almenara et al., 2019b).

In engineering education, AR has been used to improve students' understanding in different courses (Souvestre et al., 2014; Odeh et al., 2013; Kaur et al., 2019). This subject area deals with concepts that can be better explained and understood using 3D visualization instead of 2D images. The virtual interaction and manipulation of these elements can make the concepts more attractive and exciting for students (Sharma & Mantri, 2020).

Specifically, Electronics is considered a tricky subject by students (Martin-Gutierrez et al., 2015). As a result, AR technology has been utilized in this field to identify electronic components, provide design and monitoring information on electrical substations (Opriş et al., 2017), and create simulation of electronic boards with switches as AR elements (Cubillo et al., 2012; Akçayir et al., 2016). Some electronic concepts are challenging to understand because students cannot visualize what electricity is and how it works (Matcha & Awang, 2012). For example, students may not understand the current flow within the circuit or the differences between series and parallel circuits. Nevertheless, making electricity visible through Augmented Reality (AR) apps makes the subject more comprehensible and makes students understand the concepts better (Restivo et al., 2014). As a result, various apps have been developed, where electrical circuits can be configured through targets representing different components, allowing the user to observe the resulting operation (Matcha & Awang, 2012; Restivo et al., 2014; Martin-Gutierrez et al., 2015).

The use of this technology in electronics learning has been shown to improve academic results (Akçayir et al., 2016); however, technological acceptance of an AR app among students remains unexplored. Students' acceptance of AR is crucial for its successful implementation in the educational process, and understanding these dynamics will help clarify AR environments' behaviors (Esteban-Millat et al., 2018). Thus, to bridge an important gap in literature, we develop an interactive AR app to understand electrical circuits' operation and determine the factors that influence the acceptance of this technology in engineering students.

The Technological Acceptance Model (TAM) by Davis (1989) is widely used to study users' adoption of technologies (Eraslan & Kutlu, 2019). This model explains the user's behavior for accepting technology (Cabero-Almenara et al., 2019a) based on their attitudes (Huang et al., 2016) and considers the impact of certain beliefs on the *attitude toward using* and the *behavioral intention to use* a technology (Esteban-Millat et al., 2018). This model is selected because it allows determining the intention of using technology before its use becomes frequent (Kamal et al., 2020). Evidence indicates that it is a valid and robust model for explaining the intention of use in any environment (Cabero-Almenara et al., 2019a) and exploring the adoption of new technological innovations (Do et al., 2020).

TAM's predictive power lies in enabling the relationship between various context-specific factors that could influence the acceptance of a specific technology (Al-Adwan, 2020). Two of these beliefs are *technology optimism* and *technology innovativeness* (Parasuraman, 2000). The first one relates to individuals' positive perception of technology because they feel it helps them have greater control over their lives. The second one refers to a person's tendency to be a pioneer user of technology and be a leader in its use. The literature addresses impact of these variables on the intention to use (Lin et al., 2007). However, their influence has not been individually analyzed. Further whether they affect the *attitude toward use* remains to be seen.

While variables directly related to an app, such as *perceived ease of use* and *perceived usefulness*, could explain the intention to use, students' characteristics, such as their attitude toward technologies, could indicate future behavior toward them. Furthermore, it would be interesting to establish if these characteristics are influenced by the opinion of people who are important to these individuals, such as teachers, parents, or friends. Therefore, this work aims to analyze the role that *technological optimism* and *technology innovativeness* play in the acceptance of AR. That has not been previously studied in AR environments. The results may be useful to app developers and educators, who require a deeper understanding of the factors driving the acceptance of this technology (Pribeanu et al., 2017).

This paper is organized as follow. In the following section, the theoretical framework is developed, and the hypotheses are presented. The data and methods used to test these hypotheses are discussed in the methodology section. In the next section, the results are reported and discussed. Finally, conclusions, limitations, and future research perspectives are identified.

Theoretical background and hypotheses

The current research aims to establish if technological optimism and technology innovativeness can predict or explain the use of AR in education by students. This study focuses on three theoretical constructs: *subjective norm*, *technology optimism*, and *technology innovativeness*, all of which considered as determinants of *attitude toward using* and *behavioral intention to use* a technology.

Subjective norm refers to the perception of those important to the individual regarding a determined behavior (Fishbein & Ajzen, 1975). It is one of the main factors influencing *behavioral intention to use* (Ajzen, 1991). Other people's expectations, whose opinions are important to the individual, can influence their perception of the technology (Taneja et al., 2006) or their trust toward it (Wu & Chen, 2005). In an academic environment, academics and classmates' opinions can influence students' beliefs regarding technology usage (Ngafeeson, 2015). Two of these beliefs can be *technology optimism* and *technology innovativeness*. If a student's immediate circle, which comprises academics and peers, has a positive opinion about a specific technology, the student may be more likely to positively perceive the technology and incorporate it into their learning process.

Similarly, the student is likely to positively perceive their preparedness to use a technology. Given that students are willing to be pioneers in using new technologies that support their educational process, they are likely to be influenced by the university ecosystem during the early stages of the technology's adoption. Further, an individual's optimism regarding a technology is associated with their pioneer status in its use (Li & Wu, 2011; Ziyae et al., 2015; Ismail et al., 2011). Therefore, we propose the following hypotheses:

- H1: *Subjective norm* has a positive effect on *technology optimism*.
- H2: *Subjective norm* has a positive effect on *technology innovativeness*.
- H3: *Technology optimism* has a positive effect on *technology innovativeness*.

Attitude toward using refers to the user's evaluation regarding the convenience of using a determined technology (Davis, 1993). *Behavioral intention to use* refers to an individual's perception of what others think he should do about a determined behavior (Fishbein & Ajzen, 1975). The users' acceptance of a technology can be more accurately determined by *behavior of intention to use*, rather than their current usage of the technology, owing to the significant causal relationship between them (Sheppard et al., 1988). Technological optimism, which indicates the individual's preparedness to use a technology (Chung et al., 2015), is associated with their attitude to use it. Individuals have a positive attitude toward the use of a technology when they believe that it will create positive impacts in relevant aspects, including academic performance. Previous studies have indicated that this aspect can be a consistent predictor for adopting technologies (Gilly et al., 2012).

Similarly, technology pioneers rarely consider new technologies as complex or beyond their understanding. Such users are likely to regret losing the opportunity to explore new technologies (Karahanna et al., 1999). Therefore, such individuals have a more favorable attitude toward using a particular technology. Thus, the following hypotheses were formulated:

- H4: *Technology optimism* has a positive effect on *attitude toward using*.
- H5: *Technology innovativeness* has a positive effect on *attitude toward using*.
- H6: *Attitude toward using* has a positive effect on *behavioral intention to use*.

This research model is proposed in Figure 1. The model suggests the positive effect that *subjective norm* has on *technology optimism* and *technology innovativeness* as well as the positive impact that *technology optimism* and *technology innovativeness* have on *attitude toward using*. These hypotheses have not been investigated in the context of AR apps. The model also hypothesizes the positive effect of *attitude toward using* on *behavioral intention to use*, as indicated by previous studies.

App design

An AR app to analyze digital current (DC) in resistive circuits was developed. The degree of interactivity of existing apps is not high because they can only manipulate graphical objects to analyze their behavior (Matcha & Awang, 2012; Restivo et al., 2014). Therefore, our purpose was to create an app with a higher interactivity level, with real-time interaction (Aquel, 2013). Students will interact with the app by generating a simulation where stimuli generate complex responses.

The app offers five types of series and parallel circuits to choose from. Batteries, light bulbs, and resistors may be incorporated into the circuit. The app's circuits allow any configuration and simulate current flow when batteries, light bulbs, and resistors are incorporated. Users can change the voltage values of the batteries and the resistance of light bulbs and resistors. The app then calculates real-time and displays the resulting voltage and amperage (Figure 2). The app assigns a color according to the amperage's value in each branch of the circuit. A red branch indicates high amperage, an orange indicates medium amperage, yellow indicates low amperage, and gray indicates no amperage. The light bulb's light intensity depends on the amperage of the branch in which it is located. Using the loop method and applying Kirchhoff's voltage law (Floyd, 2007), the app computes the values.

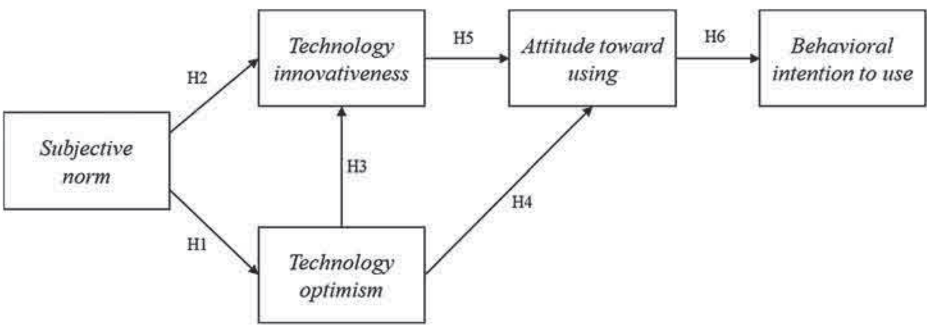

Figure 1. Research Model.

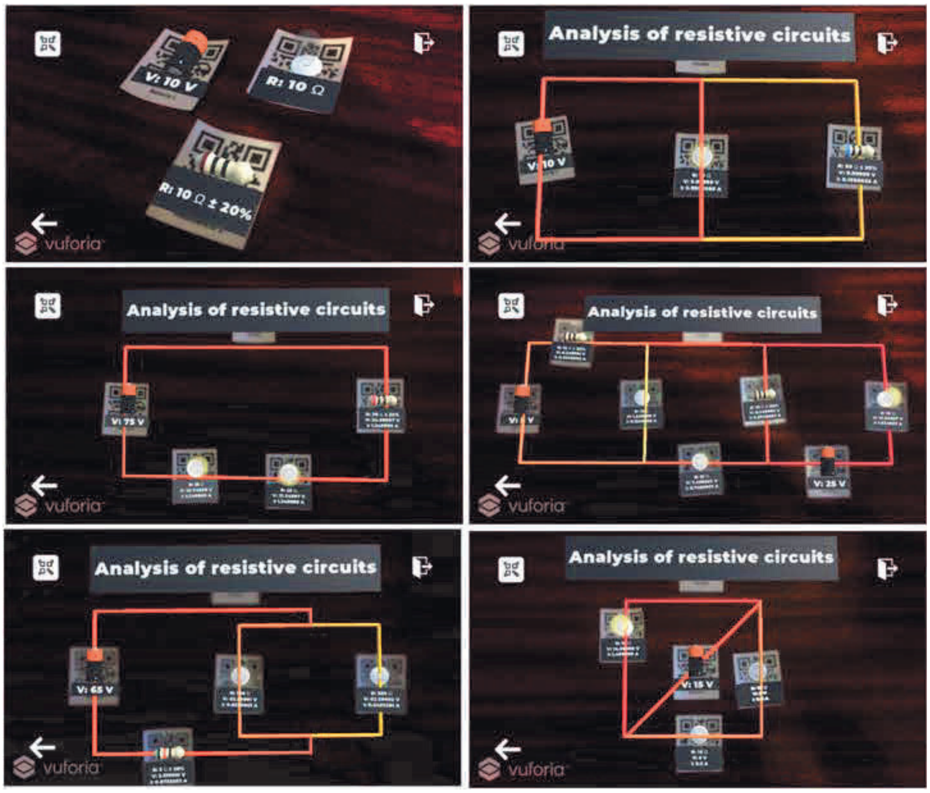

Figure 2. Interactive AR app.

The app uses an optical tracker in its operation. Circuit, batteries, light bulbs, and resistors use a QR code as a target to position each AR figure in the space. The app was developed in *Unity 3D,* using the *Vuforia SDK*. Three-dimensional objects were created with *Blender*. A QR code is used by the circuit, batteries, light bulbs, and resistors code as a target to position each AR element in the space.

The app allows students to practice with a wide range of electrical circuit configurations owing to its high interactivity level. In addition to having various types of series and parallel circuits for practice, students can freely configure them to understand the current behavior through the branches. Moreover, they can observe the variations in the amperage of the different elements. The same happens when varying the voltage of the power source or when incorporating new ones. By freely interacting with the application, the students can better understand how electricity works. Further, it provides students a tool that delivers the resulting values if they wish to develop numerical exercises.

Methodology

The model and the proposed hypotheses will be tested simultaneously using structural equations. The partial least squares technique is appropriate because it combines unobserved variables, representing theoretical concepts and data from measurements, which are then used to provide evidence on the relationships between latent variables. (Williams et al., 2009). Furthermore, the approximation involves complex models and compound variables, as stated by Sarstedt et al. (2016). Its application comprises the following steps: the adjustment of the model and the evaluation of the measurement model and the structural model (Chin, 2010). This model considers type B compound variables, as defined by Cepeda-Carrion et al. (2019). All the models are estimated and considered 5000 subsamples in the bootstrapping analysis. The software used was *Smart PLS 3.2.9* © (Ringle et al., 2015).

A literature review was conducted to construct questions regarding the selected variables. The instrument was developed using a 5-point Likert scale ranging from totally disagree (1) to totally agree (5). The studies and indicators used are shown in Table 1.

The type of sampling used was probabilistic and for convenience. The instrument was applied to third- and fourth-year students studying engineering programs at the University of NN1 (Engineering in Information Technology, Engineering in Telecommunications, Connectivity, and Networks), and the University of NN2 (Industrial Engineering, Mechanical Engineering, Engineering in Mines, Civil Engineering, Environmental Engineering, Construction Engineering). Students enrolled in these majors were selected because the academic programs included courses that worked with electrical circuits. Student participation was voluntary, and no evaluation-related incentives were given. The anonymity and strict confidentiality of the data were guaranteed.

The data collection was carried out through an online survey. Students were invited to participate via email. Survey started with a three-minute video explaining the use of the app. Subsequently, links for students to download the application from Google Play (for Android systems) and APP Store (for IOS systems) were shared. The students were able to use the app freely. Next, they were asked to complete the survey.

Results and discussion

In total, 173 students answered the survey (127 males and 46 females). Of these, 46 were industrial engineering students, 38 were information technology students, 31 were mechanical engineering students, 26 were students from mining engineering, 11 were civil engineering students, and 21 were students from other specialties.

As the loadings of the indicators of each construct are greater than 0.7, the constructs' Composite Reliabilities (CR) are also higher than 0.7, and their Average Variance Extracted (AVE) is above 0.5; thus, the requirement of reliability, convergent validity, and Variance Inflation Factor (VIF) is satisfied (Hair et al., 2016). Discriminant validity is achieved according to Fornell-Larcker and the Heterotrait – Monotrait ratio (HTMT) criterion (Henseler, 2018). The results are shown in Tables 2 and 3, respectively.

Table 4 shows the results obtained for the model. All six proposed hypotheses are accepted. Table 5 shows Squared Correlation Coefficient values (R^2), which are significant and over 0.1 (Frank & Miller, 1992) for each latent variable. The Stone-Geisser coefficient (Q^2) is also shown, which was estimated

Table 1. Studies and indicators used.

Construct	Study	Indicator
Subjective norm	Teo et al. (2008)	People whose opinions I value encourage me to use new technologies. People who are important to me help me use new technologies.
Technology optimism	Chung et al. (2015)	The products and services that use the newest technologies are much more convenient to use. I prefer to use the most advanced technology available. Technology makes my work more efficient.
Technology innovativeness	Chang et al. (2017)	If I find out that there are new technologies, I look for ways to test it. Among my classmates, I am generally the first to try new technologies. I like to experiment with new technologies.
Attitude toward using	Pantano et al. (2017)	I think using the app in classes would be positive. The app is so interesting that you want to learn more about it. It makes sense to use the app for the study of electrical circuits. The app is a good idea.
Behavioral intention to use	Balog and Pribeanu (2010)	I would like to have this app if I had to study electrical circuits. I would intend to use this app to learn about electrical circuits. I would recommend other students to use this app to study electrical circuits.

Table 2. Evaluation of the measurement model.

Construct/ indicator	VIF	Cronbach's alpha	Dijkstra–Henseler's rho	CR	AVE
Subjective norm [SN]		0.786	0.908	0.899	0.808
SN1	1.719				
SN2	1.719				
Technology optimism [TO]		0.881	0.887	0.926	0.808
TO1	2.825				
TO2	2.433				
TO3	2.282				
Technology innovativeness [TI]		0.799	0.846	0.878	0.707
TI1	1.702				
TI2	1.610				
TI3	1.890				
Attitude toward using [ATU]		0.837	0.853	0.890	0.670
ATU1	1.846				
ATU2	1.757				
ATU3	1.824				
ATU4	2.273				
Behavioral intention to use [BIU]		0.884	0.887	0.928	0.811
BIU1	2.304				
BIU2	2.520				
BIU3	2.767				

by blindfolding (Gefen et al., 2000). Values greater than 0 indicate that the variables have predictive relevance (Hair et al., 2014). The model shows predictive validity.

To assess the goodness of fit in the estimated model, we followed the procedures proposed by Dijkstra and Henseler (2015). The Standardized Root Mean Squared Residual (SRMR) for the model is lower than 0.10, indicating a good fit, as presented and defended by Williams et al. (2009) and supported by Ringle et al. (2012). The deviations are not significant because the 99 percent bootstrap quantiles of the value of the three measures —SRMR (0,048), the Unweighted Least Squares discrepancy (dULS = 0,280), and the Geodesic discrepancy (dG = 0,105) – were more significant than the original values (Henseler, 2017).

The results obtained for the model are shown in Figure 3. All hypotheses of the model are accepted. *Technology optimism* is dependent on a medium-range of *subjective norms* ($R^2 = 0.204$) (H1), likely due to the absence of other factors. However, this value is not as small, as it is explained by only one variable. Moreover, *subjective norms* have a large effect on *technological optimism* (0.452). It can be inferred that if students live in an environment that has a positive opinion about using technologies, they will perceive new technologies as tools facilitating their education. Thus, if higher education institutions highlight the virtues of using technologies in the educational process, they could generate a favorable opinion among students regarding the advantages of incorporating them.

Subjective norms and *technology optimism* have a relevant impact on *technology innovativeness* ($R^2 = 0.503$) (H2 and H3). The direct effect of *subjective norms* on *technology innovativeness* is 0.233, while *technological optimism*'s direct influence is 0.573. It can be further observed that *technology optimism* has a statistically significant complimentary mediation between *subjective norms*

Table 3. Measurement Model. Discriminant Validity

	Fornell-Larcker Criteria						Heterotrait–monotrait ratio (HTMT)				
	ATU	BIU	SN	TI	TO		ATU	BIU	SN	TI	TO
ATU	0.818					ATU					
BIU	0.790	0.901				BIU	0.899				
SN	0.286	0.263	0.903			SN	0.343	0.303			
TI	0.334	0.354	0.475	0.841		TI	0.361	0.385	0.564		
TO	0.449	0.429	0.392	0.646	0.899	TO	0.513	0.482	0.441	0.736	

Table 4. Results from the structural model.

Hypothesis	path	*t*-value	*p*-value	
H1: SN → TO	0.452	5.916	0.000	accepted*
H2: SN → TI	0.233	3.276	0.001	accepted*
H3: TO → TI	0.573	7.820	0.000	accepted*
H4: TO → ATU	0.333	3.393	0.000	accepted*
H5: TI → ATU	0.185	1.999	0.023	accepted**
H6: ATU → BIU	0.827	19.776	0.000	accepted*

* Significant $p < 0.01$; ** Significant $p < 0.05$.

Table 5. R^2-Q^2

Construct	R^2	*p*-value	Q^2
Technology innovativeness	0.503	0.000	0.271
Technology optimism	0.204	0.002	0.097
Attitude toward using	0.229	0.014	0.087
Behavioral intention to use	0.684	0.000	0.481

and *technology innovativeness*. The indirect impact of *subjective norms* on *technology innovativeness* through *technology optimism* is 0.259 (0.452*0.573). The above indicates that a large part of the effects of *subjective norms* on *technology innovativeness* is explained by *technology optimism*. This would mean that the students' pioneer status in using a technology is associated with their positive perception of the technology's usefulness. Further, the perception among the students' academic circles influences their willingness to use it.

Attitude toward using is medium dependent ($R^2 = 0.229$) on *technology optimism* and *technology innovativeness* (H4 and H5). That is due to the absence of variables not included in the analysis, such as *perceived ease of use* and *perceived usefulness*. Nonetheless, these personal characteristics (*technology optimism* and *technology innovativeness*) would moderately explain the student's *attitude toward using*. The direct effect of *technology optimism* on *attitude toward using* is 0.333, while *technological innovativeness*'s direct impact is 0.185. This is consistent with previous studies in other areas, which indicate that *attitude toward using* is influenced by *technology optimism* (Kros et al., 2011; Theotokis et al., 2008) and *technology innovativeness* (Al-Ajam & Nor, 2015; Kros et al., 2011; Lin & Chang, 2011).

Furthermore, there is a statistically significant complimentary mediation of *technology innovativeness*, between *technology optimism* and *attitude toward using*. The indirect effect is 0.106 (0.573*0.185), which indicates that only a portion of the impact of *technology optimism* and *attitude toward using* can be explained by mediation with *technology innovativeness*. It can be inferred that it is not enough for students to be pioneers in using technologies to have a positive attitude toward technologies' adoption; it is imperative that they perceive these technologies as useful. Further, their attitude toward using technologies can be influenced their respective academic

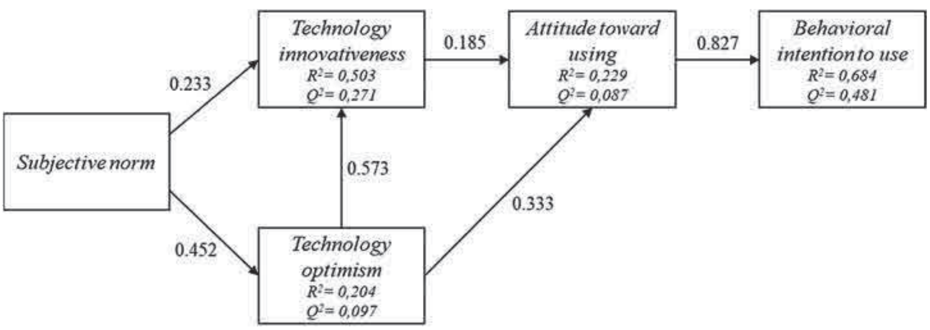

Figure 3. Resulting Research Model.

circles' perception of these technologies. Lastly, the model shows that *behavioral intention to use* strongly depends on *attitude toward using* ($R^2 = 0.684$) (H6), indicating that a student with a positive *attitude toward using* the technology would intend to use it, which ultimately indicates the effective use of the technology in classroom. This is consistent with previous studies in AR in other areas, which show that *behavioral intention to use* is powerfully explained by *attitude toward using* (Arvanitis et al., 2011; Chung et al., 2015; Mao et al., 2017; Pantano et al., 2017; Wang et al., 2016; Wojciechowski & Cellary, 2013).

Conclusion

The current study proposed a model to explain the role of *technology optimism* and *technology innovativeness* on AR's acceptance among engineering students. The model considered *subjective norms*, *technology optimism*, *technology innovativeness*, and *attitude toward using* to explain the *behavioral intention of use*. T*echnology optimism* and *technology innovativeness* have not been investigated in the context of the AR apps, which makes the current analysis unique. The proposed model and the hypotheses were tested simultaneously, using structural equations through the partial least squares technique.

Given that the intention of use represents an individual's inclination toward using a technology in the short-term (Al-Rahmi et al., 2020), we can interpret from our results that AR could be incorporated in the engineering educational processes by influencing students' characteristics.

The findings suggest that *subjective norms* have a positive effect on *technology optimism* and *technology innovativeness*. Higher education institutions must generate awareness regarding the benefits of technological tools in learning to create technology-friendly environments and promote an optimistic technological attitude. It would be convenient to create a climate that encourages AR technologies, for both students and academics, since subjective norms are continually being built. Thus, through subjective norms, students, being digital natives, can be influenced by behavior models, for example, faculty and peers, due to the influence that their environment exerts on them (Hanif et al., 2018). Higher Education institutions should establish communication and divulgation policies facilitating the successful implementation of new technologies in the teaching and learning processes. To create an environment conducive to adoption of new technologies, training in the scope and use of the technologies should be offered. It is also recommended the education institutes promote the development of such applications within campus, making them available to academics.

The attitude toward use can be influenced by technology optimism and technology innovativeness and can give higher education institutions clarity on which actions to take. Technological optimists have more favorable perceptions toward technologies and higher willingness to adopt them (Perry, 2016). Technological innovators want to be among the first to use new technologies (Cruz-Cárdenas et al., 2021). Therefore, successful AR implementation in engineering education should consider areas not previously addressed, such as its members' attitude toward new technologies and the institutional influence toward these attitudes. The use of a technology that can be perceived as beneficial can increase students' technological optimism toward this technology in an educational context. How the participation of technologically innovative students influences their peers should also be considered.

Educational institutions are training digital natives, and the AR apps allow institutions to be more efficient in the educational process. Future engineers are expected to be familiar with AR and other technologies to cope with the 4.0 industry. Future research should address factors that influence technology adoption among academics and consider relevant characteristics of the technology (e.g. interactivity levels, application stability) to analyze their influence on its acceptance. As a limitation, this study was carried out in a developing country context. However, in the future, the results can be compared to other countries under wider contexts.

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Article

Technology Acceptance of an Interactive Augmented Reality App on Resistive Circuits for Engineering Students

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Abstract: In this study, we aim to establish the factors that explain the technology acceptance of augmented reality (AR) in students' engineering education. Technology acceptance of AR apps has been insufficiently investigated. We conceive a theoretical model to explain technology acceptance by relating behavioral intention to use with the variables subjective norm, technology optimism, technology innovativeness, perceived ease of use, perceived usefulness, and attitude toward using. An interactive AR app on electrical circuits was designed to assist students to overcome their difficulties in understanding how electricity works. A theoretical model was hypothesized and tested using structural equation modeling. The study was conducted using a sample of 190 engineering students. The results demonstrate the positive effect of technology optimism and technology innovativeness on perceived usefulness and attitude toward using, respectively. Furthermore, they suggest that attitude toward using is influenced by perceived usefulness but not directly by perceived ease of use. This could mean that students would be willing to use this app if they find it useful and not just easy to use. Finally, the results illustrate that attitude toward using firmly explains behavioral intention to use, which is consistent with the findings in previous studies. These results could guide how academics and higher education centers should approach the incorporation of these technologies in classrooms.

Keywords: augmented reality; education; engineering; mobile learning; technology acceptance

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1. Introduction

The education sector can benefit significantly by incorporating information technologies and improving the academic performance of students [1,2]. However, students' resistance to new technologies can impede their successful adoption or use. Therefore, determining the factors that explain and predict acceptance of these technologies is necessary to design effective adoption strategies.

One of these technologies, augmented reality (AR), has been employed in different fields [3], from tourism and navigation to entertainment and advertisement, geometry modeling and scene construction, assembly and maintenance, information assistant management, training, and education [4].

In the education sector, AR has been adopted in several areas of knowledge [5] because it provides additional value to mobile learning objects by providing greater interactivity and an attractive learning environment [6]. The inclusion of AR technology helps students in improving their creativity, critical thinking, and problem-solving skills [7].

In engineering education, one of the areas where AR has been used is electronics [8,9]. Students frequently find it difficult to understand electricity concepts because electricity and its working mechanism are invisible [10]. Visualizing electricity through an AR app allows students to understand these concepts more intuitively [11] and improve their academic achievements [12].

Incorporating the AR technology in different stages of the educational process could also allow future engineering skills to be incorporated into Industry 4.0, which is characterized by even more digitized and optimized operations in an integrated network under the concept of industrial AR [13]. For example, companies with modern production systems currently anticipate AR apps that can support the assembly process through virtual instructions [14].

Despite these benefits, the analysis of how users accept and use various innovative technologies is lacking [15]. Technology acceptance is meant to explain technology usage behavior and is associated with behavioral intention [16]. Given this, models are used to predict or explain the behavior of individuals on the implementation of information technologies.

One of the most important models, the technology acceptance model (TAM), proposed by Davis [17], is an adaptation of the theory of reasoned action [18]. The TAM incorporates the following variables: perceived ease of use, perceived usefulness, attitude toward using, and behavioral intention to use.

Some studies have suggested the TAM's incapacity to model new scenarios. However, these studies focus on commercial applications, mainly marketing and AR apps' perceived value. Vishwakarma et al. [19], while researching an AR app in tourism, indicated that the applicability of the TAM is limited because it explains the adoption of new information and communication technologies only from the viewpoint of users and not consumers. They used the value-based adoption model [20], which considers adoption from a consumer's perspective, rather than from a technology user perspective.

Nevertheless, the extended versions of the TAM remain valid in education as apps are provided to students to support the educational process and autonomous learning. Given that the commercialization of apps is not considered, students are not treated as consumers.

The TAM has been applied to study the adoption of new information and communication technologies such as wearables [21], Google Glass [22], and AR in science [23] and geometry [24,25]. In the educational field, the TAM has been recently employed to examine the adoption of massive open online courses [26,27], digital communication [28], e-learning [29,30], mobile learning [31–33], and the use of open-source software [34].

In engineering education, only one study was found that addressed the acceptance of the AR technology using structural equation modeling to analyze the causal relationship between variables. Ibañez et al. [35] used the TAM to explore students' perceptions regarding problem-solving in electromagnetism. The results of the evaluation demonstrated that the behavioral intention to use was dependent on perceived enjoyment. However, the authors had to remove the perceived usefulness construct because of inconsistency in students' responses. The personal or environmental characteristics were not considered.

As AR technology has proven to be useful for improving academic performance, higher education institutions need to incorporate it more intensively in their teaching and learning processes. The AR technology allows the creation of virtual laboratories that can be used for different subjects, thereby optimizing the use of available resources. Further, being an app, students can download and use it freely. Based on the features provided by smartphones or tablets, each student could have a laboratory in his or her hands to experiment and perform exercises, thereby catalyzing autonomous learning processes in students. The AR technology can also promote distance learning, as students do not necessarily need to visit laboratories.

However, this scenario is not possible if the actors involved are not willing to use this technology. If the variables that influence the willingness to use technology are appropriately understood, then the actions that lead to reinforcing the disposition of certain students to use such technology can be encouraged. Thus, if an early-stage technology reveals that potential users are unlikely to accept it, appropriate interventions could be applied to achieve acceptance; otherwise, these resources could be invested in the development and implementation of other higher impact technologies.

The characteristics of the current generation of students must also be considered. Being digital natives, they are increasingly immersed in digital technologies [36]. The acceptance of technologies by digital natives requires incorporating a series of individual and relevant factors [29]. One of them is technology readiness, which comprises four dimensions: optimism and innovativeness as drivers, and discomfort and insecurity as inhibitors [37] with optimism and innovativeness being stable individual dimensions for measurement [38]. Although technology readiness dimensions have been employed in examining the technological acceptance of digital natives as consumers [39], they have not been used by incorporating them into the TAM in education. In addition, the studies on the incorporation of mobile learning in the formal educational context are scarce [40].

To address this gap, we propose an extended TAM to analyze the influence of technology optimism and technology innovativeness on AR acceptance. The study seeks to contribute to the relevant literature by determining variables that can explain and predict students' use of AR technology in engineering education. This could have implications for the policies that higher education institutions may have for adopting these technologies.

2. Theoretical Background and Hypotheses

We focus on theoretical constructs proposed by Davis [17] in the TAM: perceived ease of use, perceived usefulness, attitude toward using, and behavioral intention to use. Further, the TAM uses two theoretical constructs proposed by Parasuraman [37], technology optimism and technology innovativeness, in addition to the subjective norm, because they are related to behavioral intention to use.

Subjective norm refers to the belief that an important person or group of people will approve and support a particular behavior. It is determined by the perceived social pressure from other people to behave in a specific manner and a person's motivation to comply with those people's expectations [41]. Expectations of other people, whose opinions are important to a person, can make him or her believe that technology could improve his or her performance [42] or can render the technology trustworthy [43]. In an academic environment, students' beliefs regarding the use of technology can be influenced by the opinion of academics and classmates [44].

Technology innovativeness is defined as a person's inclination to try new information technologies [45]. It is related to people's tendency to be pioneering users of technology and be leaders in its use [37]. These users rarely consider new technologies as complex or beyond their understanding and are likely to regret losing the opportunity to explore new technologies [46]. Additionally, technology optimism refers to having a positive view of technology, including control, flexibility, convenience, and efficiency [45]. It is related to persons' positive vision toward technology because they feel they have greater control over their lives [37] and are prepared to use it [47].

Based on the above, we can infer that if a student is in an environment where technology benefits are highlighted or their use is promoted, students would believe that using these technologies can positively impact their study and encourage them to be pioneers in using these technologies. Therefore, we propose the following hypotheses:

Hypothesis 1 (H1). *Subjective norm has a positive effect on technology optimism.*

Hypothesis 2 (H2). *Subjective norm has a positive effect on technology innovativeness.*

Hypothesis 3 (H3). *Technology optimism has a positive effect on technology innovativeness.*

Perceived usefulness can be characterized as how a person thinks a particular technology will improve task performance [48], for instance, the shorter time necessary to perform a task or activity, or higher precision [49].

Further, attitude toward using refers to the user's evaluation regarding the convenience of using a determined technology [50].

If students are optimistic about the benefits that technology can provide to improve the teaching and learning process, then they may be more likely to find that specific technology easier to use, and in turn, believe that using it might be convenient and help achieve the expected results. The same could happen with a student who is a pioneer in using new technologies. With a particular technology, these students may believe that using it can be convenient and have a positive attitude toward it. Therefore, we propose the following hypotheses:

Hypothesis 4 (H4). *Technology optimism has a positive effect on perceived usefulness.*

Hypothesis 5 (H5). *Technology optimism has a positive effect on attitude toward using.*

Hypothesis 6 (H6). *Technology innovativeness has a positive effect on attitude toward using.*

The perceived ease of use is defined as the degree to which a person believes that a specific technology can be used effortlessly [49].

If students perceive that an AR app is easy to use, they might find it useful to incorporate it as a tool in their learning process. Similarly, this app was easy to use, and because of its convenience, it could also elicit a positive attitude from students.

At the same time, this positive attitude that students may have toward the app could, in turn, be explained by how useful they find incorporating it into their educational process. This leads to our next set of hypotheses:

Hypothesis 7 (H7). *Perceived ease of use has a positive effect on perceived usefulness.*

Hypothesis 8 (H8). *Perceived ease of use has a positive effect on attitude toward using.*

Hypothesis 9 (H9). *Perceived usefulness has a positive effect on attitude toward using.*

Finally, behavioral intention to use refers to an individual's perception of what others think he or she should do about a determined behavior [18]. Studies on AR have illustrated that behavioral intention to use is influenced by attitude toward using [48,51]. Thus, this leads to our next hypothesis:

Hypothesis 10 (H10). *Attitude toward using has a positive effect on behavioral intention to use.*

We propose the research model depicted in Figure 1. This model comprises an extended TAM that incorporates the variables technology optimism and technology innovativeness, which have not been previously investigated in the context of AR apps in engineering education.

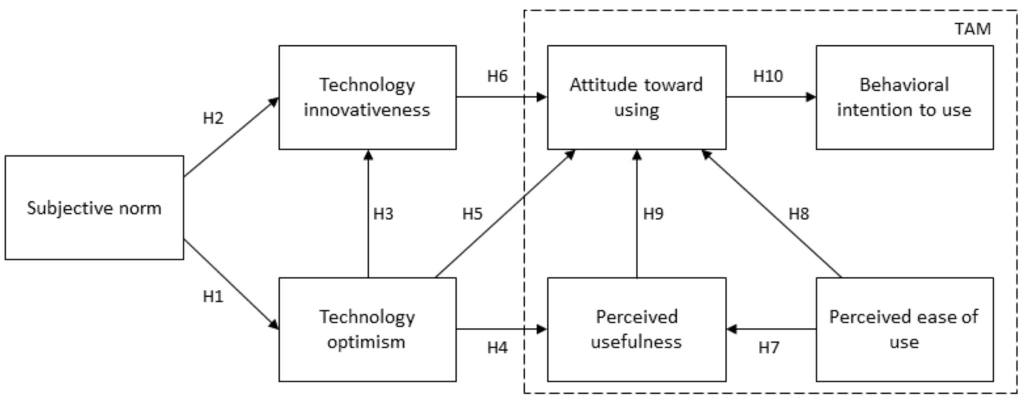

Figure 1. Research model.

3. Interactive AR App

Some apps have been developed as a support for learning electrical circuits, which help visualize electricity. Matcha and Rambli [10] developed a prototype to analyze the relationship between current and resistance in a circuit. Restivo et al. [11] developed the app "CD Circuit Puzzle." The circuit elements were used as Lego pieces to understand their operation, perceive different situations, and practice solutions. However, these apps only reach a medium degree of interaction (level III, complex interaction: the student can manipulate graphical objects to analyze their behavior [52]). Therefore, we developed an AR app that reaches a high of interactivity (level IV, real-time interaction: the student can interact in a simulation where stimuli generate complex responses [52]). This app, named "INGAR DC Analysis," analyzes direct current (DC) in resistive circuits. This app allows the user to change the batteries' voltage values and the resistance value of the light bulbs and resistors under controlled safety conditions, generating real-time amperage calculations present in the circuit.

This app can be used in theoretical classes, laboratories, or as a support tool for autonomous learning using smartphones or tablets. The AR app's purpose is to enable students to work with electrical circuits and visualize how electricity functions.

In the app, AR figures (batteries, light bulbs, and resistors) can be manipulated in serial or parallel resistive circuits by students. The app has five types of serial and parallel circuits to choose from (Figure 2).

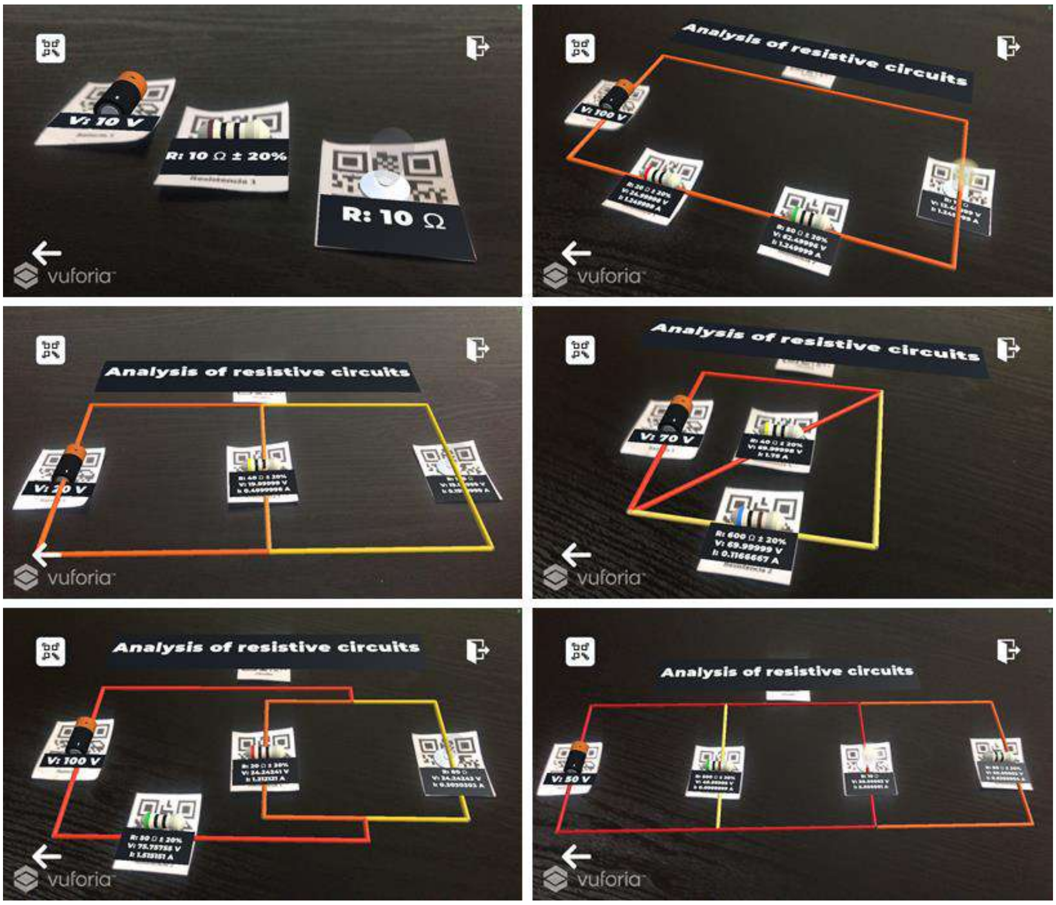

Figure 2. Interactive AR app.

By manipulating QR codes as targets, students can experience various circuit configurations by incorporating and combining batteries, light bulbs, and resistors, and varying their voltages and resistances.

With this, the app calculates and displays the resulting values of voltage and amperage of light bulbs and resistors in real time, using the loop method and applying Kirchhoff's voltage law [53].

According to the amperage value circulating in each branch of the circuit, a color is assigned. A gray branch means no amperage. A 12-color scale ranging from faint yellow to bright red was used, depending on the amperage value.

Thus, students can visualize the different intensities of current passing through each branch of the circuit and the values of amperage and voltage circulating through each light bulb or resistor.

The app was developed in Unity 3D using the Vuforia SDK. The development of the app is facilitated using prefabs, which were obtained from the SDK. Three-dimensional objects were developed with the Blender software. Batteries, resistors, and light bulbs were created as objects in AR to interact with the resistive circuit. QR codes are used by the circuit, batteries, light bulbs, and resistors code as a target to position each AR element in the space. An optical tracker for its operation is used.

4. Methodology

The model and the proposed hypotheses were simultaneously tested applying structural equations through partial least squares (PLS), using the Smart PLS 3.2.9 © software [54]. The PLS technique was adopted because it combines unobserved variables representing theoretical concepts and data from measurements, which are used to provide evidence on the relationships between latent variables [55]. This method is appropriate as the approximation includes complex models as well as compound variables [56].

The application of the PLS technique consists of different steps, with the first step being the model fit [57]. The fit test is performed for the estimated model by applying a bootstrapping process of 5000 subsamples [58]. Second, the measurement model is evaluated, and third, the fit of the model is analyzed [59]. Type B compound variables were considered for this model [60].

A review of the literature to compile the survey was conducted. Questionnaires from previous studies were used, as these questions were previously validated. A survey comprising 22 indicators was employed for data collection. Table 1 presents the studies used to adapt the questions for the constructs and indicators.

Table 1. Studies and indicators used.

Construct	Study	Indicator
Subjective norm	[61]	People whose opinions I value encourage me to use new technologies. People who are important to me help me use new technologies.
Technology optimism	[47]	The products and services that use the newest technologies are much more convenient to use. I prefer to use the most advanced technology available. Technology makes my work more efficient.
Technology innovativeness	[62]	If I discover that new technologies exist, I find ways to test them. Among my classmates, I am generally the first to try new technologies. I like to experiment with new technologies.
Perceived ease of use	[51]	I found the app to be very easy to use. The app was intuitive to use. Learning how to use the app was easy. Handling the app was easy.
Perceived usefulness	[48]	The use of the app improves learning in the classroom. Using the app during lessons would facilitate the understanding of certain concepts. I believe that the app is helpful when learning.
Attitude toward using	[51]	I think using the app in the class would be positive. The app is so interesting that you want to learn more about it. Using the app for the study of electrical circuits is logical. The app is a good idea.
Behavioral intention to use	[63]	I would like to have this app if I had to study electrical circuits. I would intend to use this app to learn about electrical circuits. I would recommend other students use this app to study electrical circuits.

The convenience sampling method—a non-probability sampling technique involving the sample being drawn from a pool of population that is easy to reach or contact—was used in this study. This type of sampling is useful for pilot testing. The sample corresponds to students studying Industrial Engineering, Mechanical Engineering, Mining Engineering, Civil Engineering, and Environmental Engineering at the University of La Serena, Chile. These branches of engineering were selected because they include subjects in which electrical circuits are taught. Student participation was voluntary, not associated with evaluation, and students were not offered extra scores to participate in the study. The prototype of the AR app was used in a guided session with the students. The pilot test has been widely used to determine behavioral intention in AR apps [23,24,51,64–67].

The research took place in March 2020. The experience and the survey were carried out in an ad hoc laboratory implemented using tablets. In the beginning, a 3 min video was shown that demonstrated how the interactive AR app worked. Then, the students experimented interacting with the app for 30 min, performing various guided exercises (similar to other studies of AR acceptance in education [35,48,68] and other fields [51,67]). Students understood different types of current intensity behaviors while practicing with serial or parallel circuits and modifying values of voltage and resistance. Moreover, students were able to interact with the app freely. At the end of the experience, the survey was conducted. Anonymity and strict confidentiality of data were guaranteed.

5. Results

The survey had 190 respondents, of which 115 were males and 75 were females. The average age was 21 years, and the students were in their third or fourth academic year. In terms of the engineering field, 77 were industrial engineering students, while 38, 32, 26, and 17 were students from mining, mechanical, civil, and environmental engineering, respectively.

As the loadings of each indicators' variance inflation factor is lower than 3.3, Cronbach's alpha and Dijkstra–Henseler's rho for each construct are greater than 0.7, the constructs' composite reliabilities are also higher than 0.7, and as their average variance extracted is above 0.5 (Table 2), reliability, convergent validity, and variance inflation factor requirements are satisfied [69–71]. Analyzing Fornell–Larcker criterion, the square root of the average variance extracted from each construct is greater than its correlation with any other construct (Table 3). The Heterotrait–Monotrait ratio of correlations is below 1.0 (Table 4). Therefore, discriminant validity is achieved according to Fornell–Larcker criterion and the Heterotrait–Monotrait ratio [58,72,73].

Table 2. Evaluation of the measurement model.

Construct/Indicator	Variance Inflation Factor	Cronbach's Alpha	Dijkstra–Henseler's Rho	Composite Reliabilities	Average Variance Extracted
Subjective norm (SN)	-	0.788	0.798	0.904	0.824
SN1	1.732	-	-	-	-
SN2	1.732	-	-	-	-
Technology optimism (TO)	-	0.773	0.774	0.869	0.688
TO1	1.757	-	-	-	-
TO2	1.752	-	-	-	-
TO3	1.411	-	-	-	-
Technology innovativeness (TI)	-	0.721	0.745	0.841	0.639
TI1	1.604	-	-	-	-
TI2	1.384	-	-	-	-
TI3	1.377	-	-	-	-

Table 2. *Cont.*

Construct/Indicator	Variance Inflation Factor	Cronbach's Alpha	Dijkstra–Henseler's Rho	Composite Reliabilities	Average Variance Extracted
Perceived ease of use (PEOU)	-	0.790	0.840	0.860	0.607
PEOU1	1.816	-	-	-	-
PEOU2	1.508	-	-	-	-
PEOU3	1.510	-	-	-	-
PEOU4	1.669	-	-	-	-
Perceived usefulness (PU)	-	0.855	0.856	0.912	0.776
PU1	1.774	-	-	-	-
PU2	2.529	-	-	-	-
PU3	2.542	-	-	-	-
Attitude toward using (ATU)	-	0.764	0.765	0.850	0.587
ATU1	1.689	-	-	-	-
ATU2	1.489	-	-	-	-
ATU3	1.494	-	-	-	-
ATU4	1.360	-	-	-	-
Behavioral intention to use (BIU)	-	0.859	0.861	0.914	0.780
BIU1	2.218	-	-	-	-
BIU2	2.591	-	-	-	-
BIU3	1.958	-	-	-	-

Table 3. Fornell–Larcker criterion.

	ATU	BIU	PEOU	PU	SN	TI	TO
ATU	0.766	-	-	-	-	-	-
BIU	0.743	0.883	-	-	-	-	-
PEOU	0.390	0.328	0.779	-	-	-	-
PU	0.611	0.423	0.560	0.881	-	-	-
SN	0.310	0.208	0.065	0.215	0.908	-	-
TI	0.296	0.311	0.105	0.115	0.332	0.800	-
TO	0.352	0.357	0.173	0.299	0.399	0.467	0.830

Note 1: ATU is attitude toward using; BIU is behavioral intention to use; PEOU is perceived ease of use; PU is perceived usefulness; SN is subjective norm; TI is technology innovativeness; and TO is technology optimism. Note 2: Fornell–Larcker criterion: Diagonal elements are the square root of the average variance extracted shared between the constructs and their measures. For discriminant validity, diagonal elements should be larger than off-diagonal elements.

Table 4. Heterotrait–Monotrait ratio.

	ATU	BIU	PEOU	PU	SN	TI	TO
ATU	-	-	-	-	-	-	-
BIU	0.915	-	-	-	-	-	-
PEOU	0.472	0.378	-	-	-	-	-
PU	0.756	0.495	0.647	-	-	-	-
SN	0.403	0.253	0.084	0.266	-	-	-
TI	0.383	0.393	0.150	0.135	0.436	-	-
TO	0.455	0.440	0.209	0.367	0.509	0.616	-

Note: ATU is attitude toward using; BIU is behavioral intention to use; PEOU is perceived ease of use; PU is perceived usefulness; SN is subjective norm; TI is technology innovativeness; and TO is technology optimism.

To assess the goodness of fit in the estimated model, we follow the procedure proposed by Dijkstra and Henseler [74]. The standardized root mean squared residual for the model should be below 0.10, as argued by Williams et al. [55] and corroborated by Ringle et al. [75]. The deviations are not significant because the 99% bootstrap quantiles of the values of the three measures, the standardized root mean squared residual (0.065), the unweighted least squares discrepancy (1.085), and the geodesic discrepancy (0.243) were more significant than the original values [58].

Table 5 lists the R^2 values, which are significant and greater than 0.1 for each of the latent variables [76]. The Stone–Geisser coefficient (Q^2) is also presented, which was estimated by blindfolding [77]. Each variable has a predictive relevance with values greater than 0, that is, high predictive validity [78]. Therefore, R^2 values and Stone–Geisser's Q^2 values have a satisfactory predictive power [70,79]. The results are consistent with those in other studies capturing TAM's predictive power in the educational setting [80,81]. The results obtained for the model are presented in Table 6 and depicted in Figure 3. Eight hypotheses are accepted, while two are rejected.

Table 5. R2–Q2.

Construct	R^2	*p*-Value	Q^2
Technology innovativeness	0.240	0.000	0.136
Technology optimism	0.162	0.001	0.106
Perceived usefulness	0.400	0.000	0.283
Attitude toward using	0.429	0.000	0.237
Behavioral intention to use	0.570	0.000	0.431

Table 6. Results from the structural model.

Hypothesis	Path	*t*-Value	*p*-Value	Supported
H1: Subjective norm → Technology optimism	0.403	6.043	0.000	Yes
H2: Subjective norm → Technology innovativeness	0.164	2.072	0.019	Yes
H3: Technology optimism → Technology innovativeness	0.400	5.107	0.000	Yes
H4: Technology optimism → Perceived usefulness	0.200	2.320	0.010	Yes
H5: Technology optimism → Attitude toward using	0.095	1.093	0.137	No
H6: Technology innovativeness → Attitude toward using	0.208	2.665	0.004	Yes
H7: Perceived ease of use → Perceived usefulness	0.564	5.606	0.000	Yes
H8: Perceived ease of use → Attitude toward using	0.103	1.088	0.138	No
H9: Perceived usefulness → Attitude toward using	0.476	4.764	0.000	Yes
H10: Attitude toward using → Behavioral intention to use	0.755	19.770	0.000	Yes

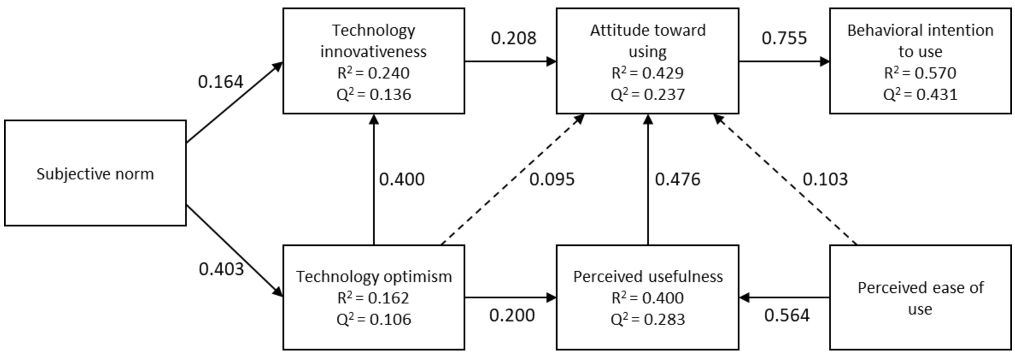

Figure 3. Resulting research model. A dashed arrow shows non-significant paths.

6. Discussion

Students' technology optimism depends on a small range of subjective norms (R^2 = 0.162; H1). This indicates that there would be other factors that help to better explain this factor.

Technology innovativeness depends moderately on subjective norms and technology optimism (R^2 = 0.240; H2 and H3). Technology optimism has a statistically significant complementary mediation between subjective norms and technology innovativeness. The direct effect of subjective norms on technology innovativeness is 0.164, while the indirect effect because of technology optimism is 0.161 (0.403 × 0.400). This implies that technology optimism explains approximately half of the impact that subjective norms have on technology innovativeness.

Perceived usefulness is dependent on technology optimism and perceived ease of use (R^2 = 0.400; H4 and H7). However, perceived ease of use (0.564) has a more significant impact than technology optimism (0.200), which indicates that the students relate the level of ease in using an app, given its usefulness to achieve more significant learning.

Attitude toward using is dependent on perceived usefulness and technology innovativeness (R^2 = 0.429; H6 and H9). Perceived usefulness (0.476) has a greater impact than technology innovativeness (0.208), implying that students must be clear about the app's usefulness for their studies and be willing to use it. However, technology optimism and perceived ease of use have no statistically significant impact on attitude toward using (H5 and H8).

Technology optimism has an indirect effect on attitude toward using, which is caused by the moderation of technology innovativeness ($0.400 \times 0.208 = 0.083$) and perceived usefulness ($0.200 \times 0.476 = 0.095$), although both these effects are negligible.

Although perceived ease of use does not have a statistically significant effect on attitude toward using, a complete mediation is produced by perceived usefulness ($0.564 \times 0.476 = 0.268$), which means that the app should not only be easy to use but also be found useful by students in improving their academic performance.

Finally, the results show that behavioral intention to use strongly depends on attitude toward using (R^2 = 0.570; H10). From the model, behavioral intention to use is expected to increase by approximately 0.755 when the attitude toward using factor increases by one.

6.1. Theoretical Contributions

In this study, we proposed an extended model of the TAM to explore factors that may influence the intention of use of an AR app by students (digital natives). Many studies have investigated the technological adoption of AR. However, few have considered the educational field, more specifically, engineering.

Moreover, few studies have emphasized students' characteristics, such as technology optimism and technology innovativeness, which are especially important because students are now digital natives. The inclusion of subjective norms also becomes relevant to determine if they influence students' evaluated characteristics, and eventually, in adopting this technology. As these are factors independent of the technology being assessed, the results can have an important implication in adopting other technologies.

Thus, we presented an extended TAM incorporating factors not studied in this context. This modification provides additional information on the acceptance of AR technology, identifying factors external to the technology and specific to the users. Particularly, in this case, the student's environment may affect the student's disposition or beliefs about technologies, which may impact the acceptance of a particular technology.

Hence, these findings help us understand the motivations and foundations that university students (digital natives) have in adopting AR technology in the future in the academic environment.

Finally, the results show that TAM remains valid and with a satisfactory predictive level when evaluated in an educational context. However, a study using an app with a poor design (e.g., less interactivity, aesthetics) may not reach the same conclusions.

As a limitation, this study was conducted in Chile in a developing country context. However, it may allow comparison and complement other studies conducted in other countries with different realities in the future.

6.2. Practical Implications

In general, the findings demonstrate that personal and environmental aspects influence the willingness to use the app. This implies that higher education institutions can influence their students to adopt new technologies and convince them that their use will help improve their academic performance. This could be achieved by disseminating the encouraging results because of the inclusion of this technology in education. The ease of use of the app influences the perception that students have about its usefulness. Therefore, this aspect should be considered when developing apps in this area.

However, the willingness of students to use this technology depends on how many students believe that they can improve their academic performance by using it and not how easy they think it is to use the app. This is consistent with the findings of Arvanitis et al. [82], who used an app in science education, and Wojciechowski et al. [48], who used an app in the field of chemistry. As the study by Ibañez et al. [35] had to remove the attitude toward using construct, their results cannot be compared. However, these findings differ from those in other areas such as tourism [47,64], where the attitude toward using is influenced by perceived ease of use and not by perceived usefulness. This is logical because when a person uses an app to study, they expect it to impact academic results positively. By contrast, when that person uses an app in a more playful environment, other factors, such as how easy it is to use that app, motivate them.

7. Conclusions

In this paper, we presented an extended TAM to determine factors that explain AR technology acceptance in engineering education. An AR app to analyze direct current in resistive circuits was developed to test the model.

The findings suggest that the academic environment can influence beliefs concerning the use of technologies and reflect how students could be affected by important role models. For example, if faculty and friends have a favorable opinion about the early adoption of technologies, students will be more willing to use new technologies. Similarly, if the student is in an environment where the benefits of using technologies by faculty and friends are valued, then he or she will have a favorable view of their use and will believe that it is convenient to use these technologies.

The findings also suggest that students would be willing to use this app if they find it useful, not just easy to use. Therefore, we suggest that the studies demonstrating that AR improves academic performance should be disseminated among educational communities.

As future work, we recommend considering relevant characteristics of this technology (e.g., interactivity levels, application stability) to analyze their influence on its acceptance. Given that we have demonstrated the direct effect of technology innovativeness in our proposed model, we also suggest investigating its moderating effect. Further, determining the variables that explain the intention of use by academics and addressing the impact on academic performance is also recommended.

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