Universidad Rey Juan Carlos

TESIS DOCTORAL

Aceptación Tecnológica de la Realidad Aumentada en la Formación de Ingenieros en Educación Superior

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Resumen

El desarrollo de la presente tesis doctoral tiene como objetivo proponer un modelo de aceptación de la tecnología de realidad aumentada, para determinar las variables que inciden en su aceptación en el ámbito del aprendizaje de circuitos eléctricos para estudiantes de ingeniería.

Como primer paso, se realizó una revisión sistemática para determinar el estado del arte del uso de la tecnología de realidad aumentada en educación en ingeniería. Los resultados de este estudio arrojan luz sobre el uso de la realidad aumentada en la educación en ingeniería. También permitieron tomar decisiones en las siguientes etapas de la investigación propuesta, al considerar diferentes aspectos, desde su uso educativo o las evaluaciones a las que ha sido sometida hasta elementos técnicos propios de esta tecnología.

Asimismo, se desarrolló una aplicación de realidad aumentada para que los estudiantes puedan analizar circuitos resistivos. Esta aplicación, con un alto nivel de interactividad, permitió a los estudiantes simular el comportamiento de circuitos en serie y en paralelo, obteniendo respuestas complejas en tiempo real, como lo son el cálculo de voltajes y amperajes que circulan por cada elemento del circuito.

Finalmente, se propusieron dos modelos teóricos para explicar la aceptación de la tecnología de realidad aumentada, relacionando la actitud hacia el uso e intención de uso con las variables *norma subjetiva*, *optimismo tecnológico*, *innovación tecnológica* en el primer modelo, y agregando las variables *facilidad de uso* y *utilidad percibida* en el segundo modelo.

En ambos modelos los resultados demuestran el efecto positivo del *optimismo tecnológico* y la *innovación tecnológica* en la *utilidad percibida* y la *actitud hacia el uso*, respectivamente. Esto sugeriría que instituciones de educación superior podrían generar conciencia sobre los beneficios de las herramientas tecnológicas en el aprendizaje para crear entornos tecnológicamente amigables y promover el uso de estas tecnologías. Además, sugieren que la actitud hacia el uso está influida por la *utilidad percibida*, pero no directamente por la *facilidad de uso percibida*. Esto podría significar que los estudiantes estarían dispuestos a utilizar esta aplicación si la encuentran útil y no solo fácil de usar, por lo que es importante difundir los beneficios que se pueden obtener en el rendimiento académico, al utilizar este tipo de aplicaciones.

Los resultados demuestran que la actitud hacia el uso explica firmemente la intención de comportamiento de uso, lo cual es coherente con estudios previos. Estos hallazgos podrían guiar la forma en que los académicos y centros de educación superior deben abordar la incorporación de estas tecnologías en el aula.

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.

Contenidos

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Acrónimos

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

Listado de publicaciones

Esta tesis por compendio está basada en el trabajo y resultados presentados en los siguientes cinco artículos científicos, referenciados en el texto como **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).

La publicación **P.I** presenta una revisión sistemática del estado del arte de la aplicación de la tecnología de realidad aumentada en educación en ingeniería. En este trabajo se busca conocer el estado del arte del uso de realidad aumentada en la enseñanza de la ingeniería, identificando debilidades y fortalezas, para identificar áreas que requirieran mayor investigación, y orientar a investigadores y desarrolladores, en mejorar la efectividad de los enfoques actuales.

La publicación **P.II** presenta el desarrollo de una aplicación de realidad aumentada para analizar la corriente continua (DC) en circuitos resistivos. Esta aplicación permite interactuar con elementos tales como baterías, bombillas y resistencias en circuitos eléctricos resistivos en serie y en paralelo, y presenta en tiempo real la intensidad de corriente y el voltaje en cada componente del circuito. Esta aplicación fue utilizada para determinar la intención de uso y las variables que influyen en la aceptación de esta tecnología.

La publicación **P.III** propone determinar la *intención de uso* de la tecnología de realidad aumentada en estudiantes de ingeniería. Esta parte del estudio contempló estudiantes que utilizaron la aplicación de manera autónoma, así como otros que participaron de una sesión presencial guiada.

La publicación **P.IV** propone determinar si las *normas subjetivas*, el *optimismo tecnológico* y la *innovación tecnológica* pueden explicar y predecir el uso de la realidad aumentada en el área de educación en ingeniería. En este trabajo, se presenta un modelo que incluye las variables antes mencionadas. El experimento se realizó de forma online con una muestra de 173 estudiantes.

La publicación **P.V** propone determinar la aceptación tecnológica de la tecnología de realidad aumentada en estudiantes de ingeniería. En este trabajo, se presenta un modelo TAM extendido, incorporando las variables *normas subjetivas*, *optimismo tecnológico*, *innovación tecnológica*, *facilidad de uso* y *utilidad percibida*. El experimento se realizó de forma presencial con una muestra de 190 estudiantes.

En todas las publicaciones **P.I – P.V**, el autor de esta tesis fue el responsable de escribir los manuscritos, desarrollar los modelos, desarrollar la aplicación de realidad aumentada utilizada, y llevar a cabo los experimentos. Los coautores contribuyeron con sugerencias en las siguientes etapas: conceptualización, metodologías, análisis formal, escritura y revisión.

Capítulo 1: Introducción

En años recientes, las tecnologías emergentes han ofrecido nuevas oportunidades al sector educativo, mejorando entre otros aspectos el desempeño académico (Akçayir et al., 2016), debido a que brinda la oportunidad de aprender de manera más eficiente y efectiva a través de una forma de enseñanza centrada en el estudiante (Al-Maroof & Al-Emran, 2018).

Una de estas tecnologías es la realidad aumentada (Augmented Reality: AR), que permite integrar objetos virtuales, a menudo en tres dimensiones (3D), con escenarios reales en tiempo real (Billinghurst & Duenser, 2012). Esta tecnología también permite mostrar información adicional en un contexto dado (Azuma, 1997) o instrucciones que ayuden a realizar un proceso (Feiner et al., 1993). Mientras que la tecnología de realidad virtual (Virtual Reality: VR) envuelve completamente al usuario en un entorno virtual, la realidad aumentada complementa la realidad en lugar de reemplazarla por completo (Azuma et al., 2001).

El uso de la tecnología de realidad aumentada en el aula ha logrado una participación más activa por parte de los estudiantes (Matcha & Rambli, 2012), aumentando su interés y motivación por aprender (Ayala Alvarez et al., 2017), contribuyendo a la mejora de su experiencia de aprendizaje. Esta tecnología también ha aumentado el rendimiento académico de los estudiantes, debido a su capacidad para permitir una comprensión rápida de problemas espaciales y relaciones complejas (Cheng et al., 2018).

En consecuencia, la realidad aumentada puede considerarse como una tecnología prometedora para la educación en ingeniería, ya que tiene el potencial de ayudar en el aprendizaje de estructuras y comportamientos complejos con propiedades no visibles que se pueden encontrar en esa disciplina (Nesterov Aleksandr et al., 2017). Así mismo, la incorporación de esta tecnología en esta área disciplinar puede favorecer las capacidades de los futuros ingenieros para incorporarse a la industria 4.0. Este tipo de industria se caracteriza por operaciones cada vez más digitalizadas y optimizadas que se integran en redes bajo el concepto de realidad aumentada industrial (Industrial Augmented Reality: IAR) (Fraga-Lamas et al., 2018). Es importante señalar que IAR es una de las tecnologías clave señaladas por los nuevos paradigmas de la industria 4.0 para mejorar procesos industriales y maximizar la eficiencia de los trabajadores (Vidal-Balea et al., 2020), por lo que incorporar esta tecnología en la educación en ingeniería podría no solo afectar al rendimiento académico de los estudiantes a corto plazo, sino también proporcionarles habilidades a largo plazo para ingresar con éxito al mercado laboral de una industria cada vez más digitalizada.

Una de las áreas de ingeniería en la que se ha utilizado la realidad aumentada para su enseñanza es la electrónica. En ella, los estudiantes encuentran algunos conceptos difíciles de entender, como la electricidad, ya que su comportamiento no es visible en los circuitos eléctricos (Matcha & Rambli, 2012). Por lo tanto, hacer visible la electricidad a través de aplicaciones de realidad aumentada hace que este tema sea más comprensible y facilita que los estudiantes comprendan mejor estos conceptos (Restivo et al., 2014).

No obstante, a pesar de los beneficios que manifiestan estas tecnologías innovadoras, faltan estudios que analicen su aceptación por parte de usuarios (Rodrigues et al., 2019). Además, la aceptación tecnológica de la realidad aumentada entre los estudiantes sigue sin explorarse, siendo crucial para su implementación exitosa en el proceso educativo. Asimismo, comprender estas dinámicas ayudarán a aclarar los comportamientos que tiene estos usuarios con dicha tecnología (Esteban-Millat et al., 2018).

Teniendo todos estos antecedentes a la vista, la pregunta de investigación principal de la presente tesis es la siguiente:

¿Qué variables influyen en que los estudiantes de ingeniería acepten la tecnología de la realidad aumentada en su proceso formativo?

Por lo tanto, el objetivo principal de la tesis presentada es proponer un modelo de aceptación de la tecnología de realidad aumentada, que incluya las variables que inciden en la aceptación de su uso por parte de estudiantes, en el ámbito del aprendizaje de circuitos eléctricos en ingeniería. El entendimiento de estas variables debiera permitir a académicos universitarios y a instituciones de educación superior establecer políticas para incentivar el uso educativo de esta tecnología en beneficio del rendimiento académico de los estudiantes.

A continuación, se presentan: la motivación para realizar la investigación en la presente tesis, en la sección 1.1; los objetivos, preguntas de investigación e hipótesis propuestos, en la sección, 1.2; las principales contribuciones que se desprenden de este estudio en la sección 1.3; y el resumen de los capítulos de la tesis en la sección 1.4.

1.1 Motivación

El desarrollo de esta tesis doctoral tiene dos motivaciones. La primera es desarrollar una aplicación con una tecnología de vanguardia, para apoyar los procesos de enseñanza y aprendizaje en estudiantes de ingeniería. El desarrollo se centró en la asignatura de electromagnetismo, más específicamente en circuitos eléctricos, debido a la dificultad que los estudiantes tienen para comprender conceptos relacionados con la electricidad (Matcha & Rambli, 2012), ya que su comportamiento es invisible. Además de producir una mejora en el rendimiento académico de los estudiantes, la realidad aumentada puede incidir positivamente en la actitud de los estudiantes hacia esta asignatura, debido a su participación en actividades en el aula de un carácter más lúdico.

La segunda motivación para realizar esta tesis es incorporar la tecnología de realidad aumentada en el quehacer de futuros ingenieros, debido a que ésta forma parte del gran abanico de tecnologías relacionadas con la industria 4.0 y la transformación digital (Vidal-Balea et al., 2020). Si los estudiantes incorporan estas tecnologías en etapas tempranas de su formación universitaria, tendrán mayores competencias cuando se enfrenten en el campo laboral.

No obstante, la realidad aumentada no podría usarse de forma eficaz si los estudiantes no tuvieran intención de usar estas tecnologías, y si las universidades no entienden las ventajas de integrarlas en su entorno de aprendizaje (Lima et al., 2022).

1.2 Objetivos, preguntas de investigación e hipótesis

Considerando el problema a resolver y las motivaciones presentadas, la pregunta de investigación (**RQ**) principal abordada en las publicaciones incluidas **(P.I – P.V)** es: **¿Qué variables influyen para que estudiantes de ingeniería acepten incorporar la tecnología de realidad aumentada en su formación?** Para responder a esta cuestión, se han planteado los siguientes objetivos, preguntas de investigación y/o hipótesis asociadas a cada uno de los capítulos de esta investigación.

Para la primera parte de la investigación **(P.I)**, se planteó el siguiente objetivo y preguntas de investigación:

O_I	**:**	Conocer el estado del arte del uso de la tecnología de realidad aumentada en educación en ingeniería.
RQ_{I-1}	**:**	¿En qué asignaturas de ingeniería se ha usado realidad aumentada?
RQ_{I-2}	**:**	¿En qué actividades educativas en ingeniería se han usado aplicaciones de realidad aumentada?
RQ_{I-3}	**:**	¿Cómo se ha evaluado el impacto de las aplicaciones de realidad aumentada en la educación en ingeniería?
RQ_{I-4}	**:**	¿Cuáles son las características técnicas principales de las aplicaciones de realidad aumentada utilizadas en la educación en ingeniería?
RQ_{I-5}	**:**	¿Qué grado de interactividad presentan las aplicaciones de realidad aumentada utilizadas en la educación en ingeniería?

Para llevar a cabo la evaluación de los modelos propuestos más adelante, fue necesario cumplir con los siguientes dos objetivos:

O_{II}	**:**	Desarrollar una aplicación de realidad aumentada.
O_{III}	**:**	Determinar la intención de uso de la aplicación desarrollada.

Esta parte del estudio buscaba desarrollar aplicación para el análisis de circuitos eléctricos resistivos en serie y paralelo que permitiera interactuar con baterías, bombillas y resistencias, presentando en tiempo real la intensidad de corriente y el voltaje en cada componente del circuito **(P.II)**, para posteriormente medir la intención de uso por parte de los estudiantes de esta aplicación **(P.III)**.

A continuación, se dio curso a las siguientes etapas. Así, el objetivo e hipótesis planteados para la siguiente parte de la investigación **(P.IV)** son los siguientes:

O_{IV} : Analizar el papel que desempeñan el optimismo y la innovación tecnológicos en la aceptación de la tecnología de realidad aumentada en el área de educación en ingeniería.

H_{IV-1} : Las *normas subjetivas* tienen un efecto positivo en el *optimismo tecnológico*.

H_{IV-2} : Las *normas subjetivas* tienen un efecto positivo en la *innovación tecnológica*.

H_{IV-3} : El *optimismo tecnológico* tiene un efecto positivo en la *innovación tecnológica*.

H_{IV-4} : El *optimismo tecnológico* tiene un efecto positivo en la *actitud hacia el uso*.

H_{IV-5} : La *innovación tecnológica* tiene un efecto positivo en la *actitud hacia el uso*.

H_{IV-6} : La *actitud hacia el uso* tiene un efecto positivo en la *intención de uso*.

Las motivaciones y justificaciones de las hipótesis planteadas pueden encontrarse en extenso en la publicación **P.IV**. Esta parte de la investigación se realizó en línea, usando la aplicación los estudiantes de forma autónoma. El modelo propuesto se muestra en la Figura 1.

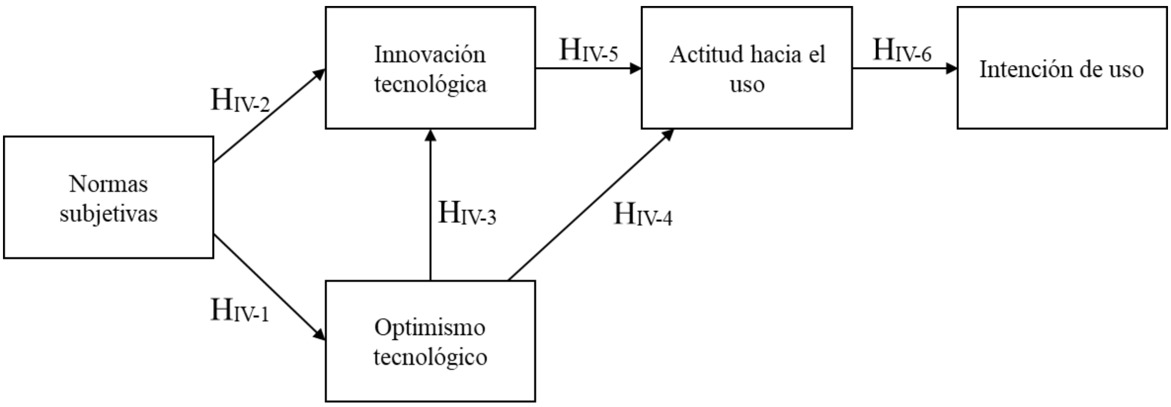

Figura 1: Primer modelo propuesto: evaluación en línea.

Finalmente, para la última parte de la investigación **(P.V)**, se planteó el siguiente objetivo con sus respectivas hipótesis, presentados a continuación:

O_V	**:**	Determinar las variables que puedan explicar y predecir el uso de esta tecnología por parte de los estudiantes de ingeniería.
$H_{V\text{-}1}$	**:**	Las *normas subjetivas* tienen un efecto positivo en el *optimismo tecnológico*.
$H_{V\text{-}2}$	**:**	Las *normas subjetivas* tienen un efecto positivo en la *innovación tecnológica*.
$H_{V\text{-}3}$	**:**	El *optimismo tecnológico* tiene un efecto positivo en la *innovación tecnológica*.
$H_{V\text{-}4}$	**:**	El *optimismo tecnológico* tiene un efecto positivo en la *utilidad percibida*.
$H_{V\text{-}5}$	**:**	El *optimismo tecnológico* tiene un efecto positivo en la *actitud hacia el uso*.
$H_{V\text{-}6}$	**:**	La *innovación tecnológica* tiene un efecto positivo en la *actitud hacia el uso*.
$H_{V\text{-}7}$	**:**	La *facilidad de uso* tiene un efecto positivo en la *utilidad percibida*.
$H_{V\text{-}8}$	**:**	La *facilidad de uso* tiene un efecto positivo en la *actitud hacia el uso*.
$H_{V\text{-}9}$	**:**	La *utilidad percibida* tiene un efecto positivo en la *actitud hacia el uso*.
$H_{V\text{-}10}$	**:**	La *actitud hacia el uso* tiene un efecto positivo en la *intención de uso*.

En la publicación **P.V**, se encuentran las motivaciones y justificaciones para cada una de las hipótesis planteadas. En esta parte de la investigación se planteó realizar una evaluación presencial guiada. El modelo propuesto en este caso se muestra en la Figura 2.

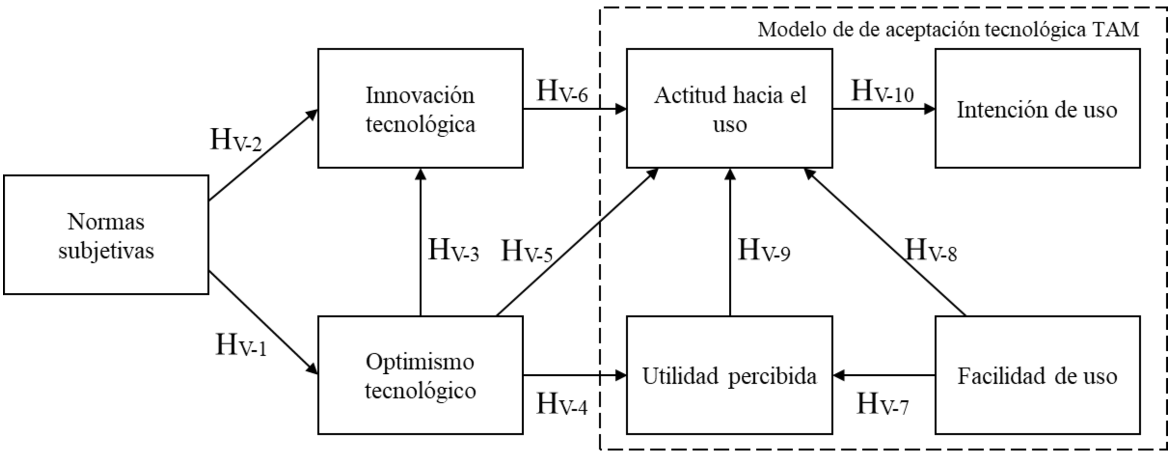

Figura 2: Segundo modelo propuesto: evaluación presencial.

1.3 Contribuciones

Las principales contribuciones de esta tesis por compendio son las siguientes, correspondientes a las cinco publicaciones antes mencionadas:

C_1 : Una revisión del estado del arte del uso de la tecnología de realidad aumentada en ingeniería, que incluye la identificación de fortalezas y debilidades de esta tecnología, las áreas donde se requiere más investigación y sugerencias a investigadores y desarrolladores de aplicaciones para mejorar la eficacia en su implementación. Esta contribución es presentada en **P.I**.

C_2 : Una aplicación desarrollada con tecnología de realidad aumentada y con un alto grado de interactividad, que permite apoyar el aprendizaje de la electrónica por parte de estudiantes de ingeniería. Esta contribución es presentada en **P.II**.

C_3 : Una evaluación de la *intención de uso* de la aplicación desarrollada, mediante una evaluación en línea de forma autónoma por parte de 190 estudiantes y una evaluación presencial guiada con 124 estudiantes. En ambos casos la aplicación muestra una alta *intención de uso*. Esta contribución es presentada en **P.III**.

C_4 : Un modelo de aceptación tecnológica de la realidad aumentada validado, que determina el papel que juegan el *optimismo tecnológico* y la *innovación tecnológica* en la aceptación de esta tecnología, lo cual no se había investigado en el contexto de aplicaciones de realidad aumentada. Este estudio constó con una muestra de 173 estudiantes. Esta contribución es presentada en **P.IV**.

C_5 : Un modelo TAM extendido de aceptación tecnológica de la realidad aumentada validado, cuyos resultados podrían guiar a académicos y directivos de educación superior, en la incorporación de esta tecnología a procesos educativos. Esta parte del estudio constó con una muestra de 190 estudiantes. Esta contribución es presentada en **P.V**.

En general, las contribuciones teóricas de esta tesis son dos modelos de aceptación de la tecnología de realidad aumentada, en dos contextos diferentes, para explorar los factores que podrían influir en la intención de uso de la tecnología de realidad aumentada por parte de los estudiantes de ingeniería. Por otra parte, las implicancias prácticas de estos resultados, además del desarrollo de una aplicación en realidad aumentada que puede ser utilizada para el aprendizaje de circuitos eléctricos, fue la de entregar un insumo a las instituciones de educación superior, para que estas puedan incentivar en sus estudiantes y en todo el ecosistema educativo, la utilización de tecnologías emergentes en el proceso enseñanza aprendizaje.

1.4 Estructura del documento

Esta tesis por compendio está compuesta por cinco capítulos e incluye cinco publicaciones: **P.I – P.V**. El contenido de cada uno de los capítulos se resume a continuación:

Capítulo 1	**:**	En este capítulo se presentan la introducción y motivación de la tesis, e incluye las preguntas de investigación, hipótesis y objetivos que se proponen, así como las contribuciones realizadas.
Capítulo 2	**:**	Se presenta un estado del arte de la utilización de la tecnología de realidad aumentada en la educación de futuros ingenieros, así como se abordan estudios que se han realizado para analizar los factores que pueden influir en la aceptación de la tecnología de realidad aumentada en su utilización.
Capítulo 3	**:**	Las metodologías utilizadas son introducidas en este capítulo, tanto las utilizadas en la revisión sistemática como en la construcción y validación de los modelos propuestos de aceptación tecnológica.
Capítulo 4	**:**	Se presentan los resultados de esta tesis. Los resultados principales publicados en **P.I – P.V** son exhibidos y discutidos, así como las contribuciones generales del estudio.
Capítulo 5	**:**	En el capítulo final se presentan las conclusiones generales de esta tesis doctoral y se realiza una propuesta de estudios futuros.

Capítulo 2: Revisión de la literatura

La realidad aumentada es una tecnología emergente que ha demostrado su potencial en diversos campos, incluyendo la educación. En particular, su aplicación en la educación de futuros ingenieros ha sido objeto de un gran interés debido a su capacidad para mejorar la comprensión y retención del conocimiento en áreas temáticas específicas.

A continuación, se resume el estado del arte de la utilización de la tecnología de realidad aumentada en educación, y se identifican modelos de aceptación tecnológica existentes, con su aplicación a esta tecnología en particular.

2.1 Realidad aumentada en educación

En la última década, cada vez se han usado más las aplicaciones de realidad aumentada. Se han reportado un número creciente de experiencias y experimentos de usuarios en diferentes áreas, incluyendo la educación (Dey et al., 2018).

Se han realizado diversas revisiones sistemáticas sobre el uso de la realidad aumentada en educación, tanto en general (Akçayır & Akçayır, 2017; Bacca et al., 2014; da Silva et al., 2019; Ibáñez & Delgado-Kloos, 2018; Pellas et al., 2019) como en campos específicos, por ejemplo, para la capacitación de procedimientos quirúrgicos en medicina (Barsom et al., 2016; Guha et al., 2017; Meola et al., 2017; Pelargos et al., 2017; Yoon et al., 2018). También encontramos revisiones sistemáticas sobre el uso de la realidad aumentada en operaciones de mantenimiento industrial (Palmarini et al., 2018) y sobre la usabilidad de aplicaciones de realidad aumentada (Dey et al., 2018).

Se pueden encontrar cinco revisiones sistemáticas de realidad aumentada en áreas educativas, que comentamos brevemente.

El primer estudio (Bacca et al., 2014) investiga ciertos factores, como los usos, ventajas, limitaciones, efectividad, desafíos y características de la realidad aumentada en entornos educativos. El objetivo principal de estas aplicaciones en realidad aumentada ha sido explicar un tema de interés, proporcionando información adicional. Ha sido efectivo en mejorar el rendimiento académico, la motivación, el compromiso y las actitudes positivas de los estudiantes. El estudio también identifica algunas limitaciones de la tecnología, incluyendo dificultades para mantener la información superpuesta, prestar demasiada atención a la información virtual y considerar la realidad aumentada como una tecnología invasiva.

El segundo estudio tiene como objetivo analizar el uso y las ventajas de las tecnologías de realidad aumentada en entornos educativos (Akçayır & Akçayır, 2017). La ventaja más frecuentemente reportada de esta tecnología es la promoción de mejoras en el logro del aprendizaje. Algunos de los desafíos destacados incluyen su usabilidad y problemas técnicos frecuentes.

En ciencia, tecnología, ingeniería y matemáticas (Science, Technology, Engineering y Mathematics: STEM), el tercer estudio busca determinar las características de las aplicaciones educativas de realidad aumentada, sus procesos de instrucción asociados y los resultados de aprendizaje observados (Ibáñez & Delgado-Kloos, 2018). Este estudio concluye que las aplicaciones de realidad aumentada deben contener características destinadas a adquirir las competencias necesarias de las disciplinas STEM y proporcionar un andamiaje metacognitivo y soporte experimental para actividades de aprendizaje basadas en la investigación.

El cuarto estudio es una revisión sistemática de la evaluación de herramientas de realidad aumentada para la educación (da Silva et al., 2019). La mayoría de los resultados (entre los que se encuentran los resultados de aprendizaje y usabilidad) son positivos. Sin embargo, la mayoría de los estudios carecen de la incorporación del profesor como diseñador instruccional y el uso de múltiples métricas para evaluar las ganancias educativas.

El quinto estudio aborda la realidad aumentada en la educación primaria y secundaria a través del aprendizaje basado en juegos (Pellas et al., 2019). Este estudio concluye que este tipo de tecnología puede influir en la adquisición de habilidades de los estudiantes, transferir conocimientos, aumentar su interés en las materias y mejorar sus habilidades digitales.

Los cinco estudios sugieren seguir profundizando las investigaciones sobre los efectos de las aplicaciones de realidad aumentada en la construcción del conocimiento. Además, recomiendan explorar los procesos de aprendizaje presentes en diferentes entornos educativos y con diversas poblaciones de estudiantes. En general, la realidad aumentada en educación comprende aplicaciones de exploración (por ejemplo, libros aumentados) y juegos (Ibáñez & Delgado-Kloos, 2018). En este último aspecto, el aprendizaje basado en juegos ha ganado rápidamente impulso al permitir nuevos enfoques de enseñanza en la educación primaria y secundaria (Pellas et al., 2019).

Por otro lado, la ingeniería se ocupa del diseño y construcción de artefactos artificiales. Comprender tales artefactos no es tarea fácil, ya que pueden tener estructuras complejas en tres dimensiones, con propiedades no visibles. La tecnología de realidad aumentada tiene el potencial de ayudar a comprender la estructura y el comportamiento de dichos artefactos. Por lo tanto, la realidad aumentada puede considerarse como una tecnología prometedora para la educación en ingeniería (Nesterov Aleksandr et al., 2017).

2.2 Aceptación tecnológica

Los rasgos de personalidad y las actitudes sociales juegan un rol importante en explicar y predecir el comportamiento humano (Ajzen, 1991). Básicamente, el comportamiento de una persona está en función de información relevante y de las creencias de esa persona. Si bien una persona puede tener muchas creencias relacionadas a un comportamiento dado, sólo un pequeño número de ellas pueden influirle (Miller, 1956). Lo anterior también responde a la relación de las personas con las tecnologías.

La aceptación tecnológica pretende explicar específicamente el comportamiento que una persona puede tener hacia el uso de sistemas computacionales (Davis et al., 1989). Está relacionada con la *intención de uso*, la que se define como la probabilidad subjetiva de que una persona lleve a cabo un comportamiento específico (Fishbein & Ajzen, 1975). Cuando la situación le proporciona a la persona completo control sobre su desempeño conductual, la *intención de uso* por sí sola, debería ser suficiente para predecir el comportamiento (Ajzen, 1991).

A continuación, se presentan los modelos más importantes para predecir o explicar el comportamiento de las personas en la adopción de tecnologías de la información.

Davis en 1986, propuso el *Modelo de Aceptación Tecnológica* (Technology Acceptance Model: TAM) (Davis, 1986; Davis et al., 1989) (Figura 3) como una adaptación de la *Teoría de la Acción Razonada* (Theory of Reasoned Action: TRA), modelo propuesto para explicar específicamente el comportamiento en el uso de sistemas computacionales (Fishbein & Ajzen, 1975). La teoría de la acción razonada explicaba la *intención de uso* mediante la *actitud hacia el uso* y *normas subjetivas*. Sin embargo, el modelo de aceptación tecnológica proponía que las *normas subjetivas* no tendrían una directa influencia en la *actitud hacia el uso*. La *actitud hacia el uso*, así como el *uso*, podrían ser explicadas por la *facilidad de uso* y la *utilidad percibida*. Posteriormente se han propuesto dos extensiones al modelo: TAM 2 (Venkatesh & Davis, 2000) (Figura 4) y TAM 3 (Venkatesh & Bala, 2008) (Figura 5) los cuales incorporan otros factores para explicar de mejor forma la *intención de uso*.

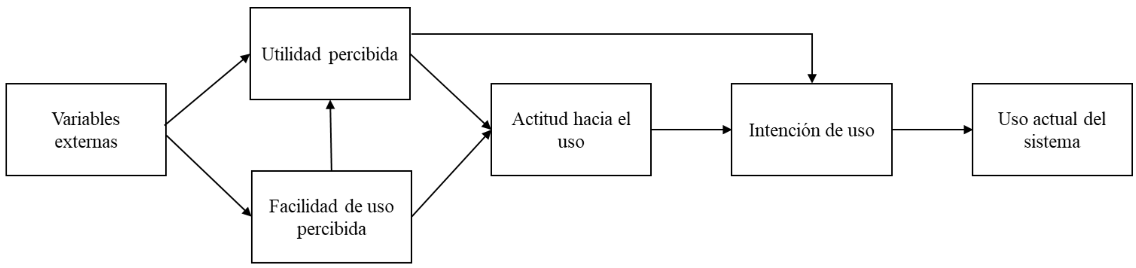

Figura 3: Modelo TAM.

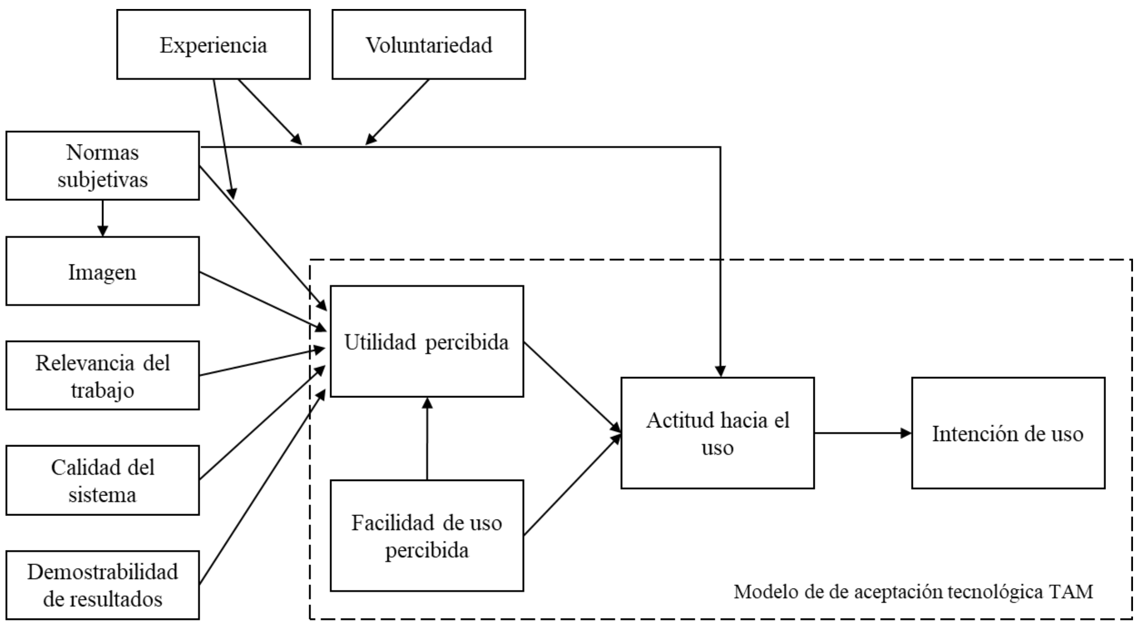

Figura 4: Modelo TAM 2.

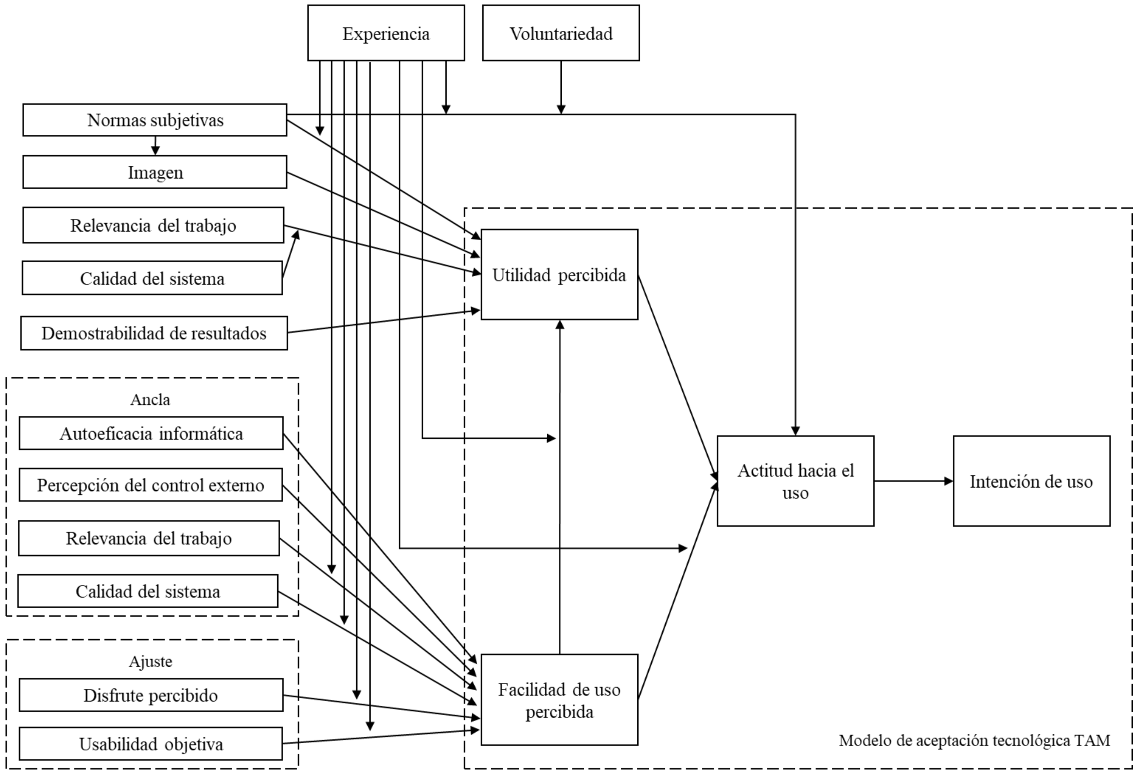

Figura 5: Modelo TAM 3.

Por su parte, Parasuraman propuso el *Modelo de la Disposición hacia la Tecnología* (Technology Readiness: TR) (Figura 6), para explicar la aceptación tecnológica (Parasuraman, 2000). Este modelo está compuesto por cuatro dimensiones: *optimismo tecnológico* e *innovación tecnológica* como impulsores de la disposición tecnológica, mientras que la *incomodidad* y la *inseguridad* se indicaron como elementos inhibidores. Sin embargo, estudios posteriores sugieren al *optimismo tecnológico* y la *innovación tecnológica* como dimensiones individuales estables para la medición de la disposición hacia la tecnología (Berger, 2009; Liljander et al., 2006; Taylor et al., 2002).

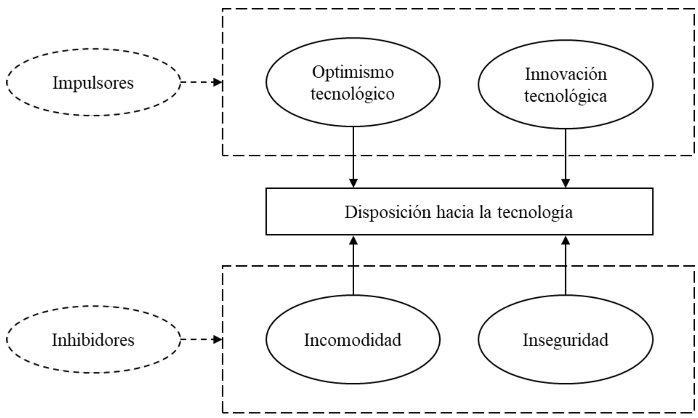

Figura 6: Modelo TR.

Venkatesh et al. propusieron en el año 2003 la *Teoría Unificada de la Aceptación y el Uso de la Tecnología* (Unified Theory of Acceptance and Use of Technology: UTAUT) (Venkatesh et al., 2003) (Figura 7) y en el año 2012 una extensión de esta: UTAUT 2 (Venkatesh et al., 2012) (Figura 8), con el propósito de integrar varios modelos existentes.

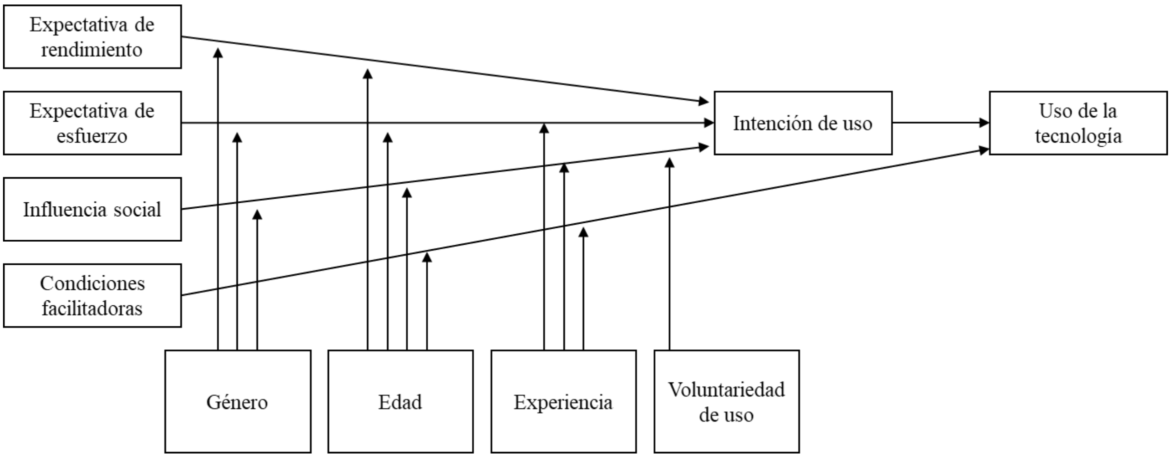

Figura 7: Modelo UTAUT.

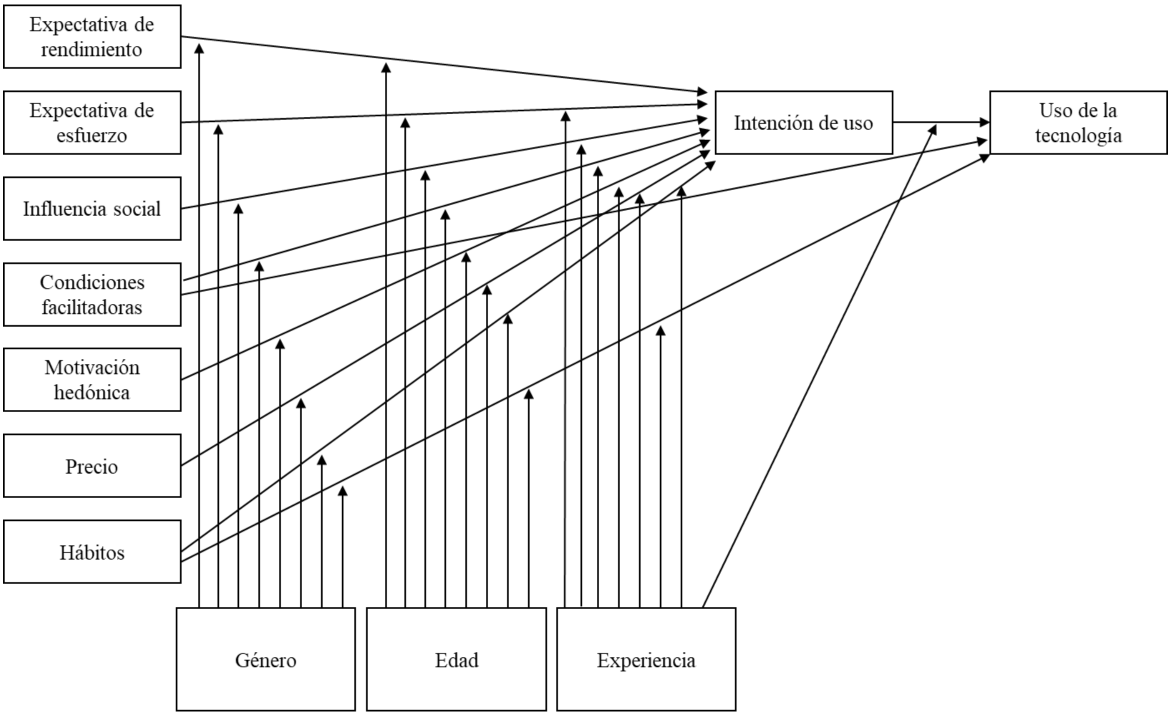

Figura 8: Modelo UTAUT 2.

Lin, Shih and Sher en 2007 propusieron el *Modelo de Aceptación y Disposición hacia la Tecnología* (Technology Readiness and Acceptance Model: TRAM) (C.-H. Lin et al., 2007) (Figura 9), el cual incorporó el modelo TR como constructo en el modelo TAM.

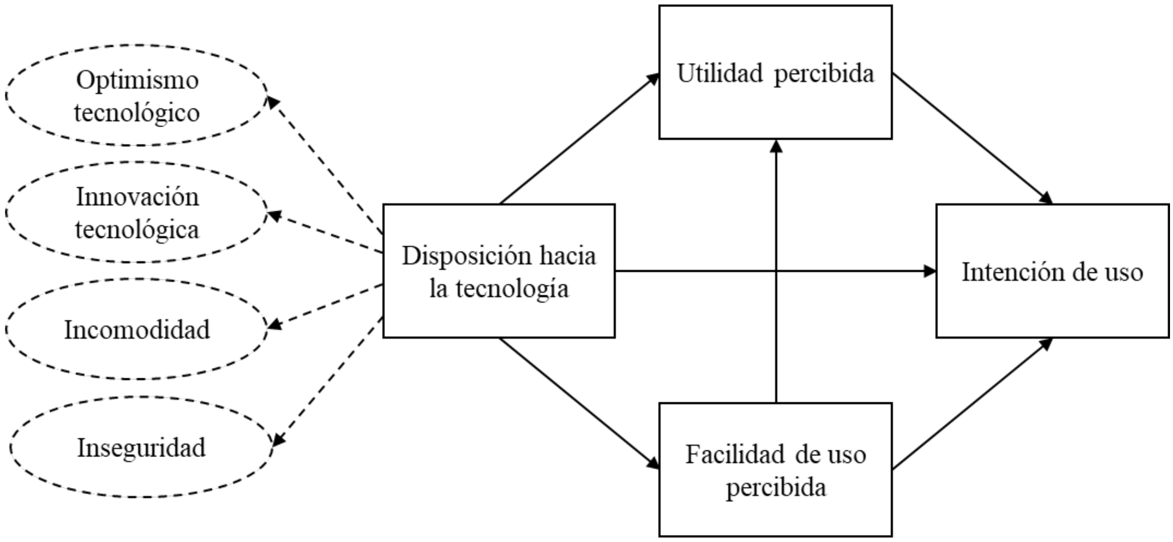

Figura 9: Modelo TRAM.

En cuanto a las tecnologías de realidad virtual y realidad aumentada, se han propuesto dos modelos. Oh and Yoon propusieron el *Modelo de Aceptación de Tecnologías Hápticas* (Haptic Enabling Technology Acceptance Model: HE-TAM) (Oh & Yoon, 2014) (Figura 10), que combina TAM con la *Teoría de la Innovación y la Difusión* (Innovation and Diffusion Theory: IDT) (Rogers, 1983). Este nuevo modelo incorpora el constructo *presencia* como experiencia informática mediada por la realidad virtual. Finalmente, Alqahtani and Kavakli en 2017 propusieron el *Marco de Aceptación de la Tecnología AR* (AR Technology Acceptance Framework: ART) (Alqahtani & Kavakli, 2017) (Figura 11), que integra UTAUT con la *Teoría de los Factores de Éxito y Motivación de los Sistemas de Información* (IS Success Factors and Motivation Theory) (DeLone & McLean, 1992). Incorpora entre otros constructos, la calidad de la información y del sistema para explicar su satisfacción y uso. Este modelo se centra en las características del sistema, no así en las características de las personas que utilizarían el sistema para explicar la intención de uso.

Estudios previos han cuestionado la capacidad del modelo de adopción de tecnología TAM para explicar nuevos escenarios. Sin embargo, estos estudios se centran en aplicaciones comerciales, especialmente en el campo del marketing y del valor percibido de aplicaciones de realidad aumentada. Un estudio reciente que investigó sobre el uso de una aplicación de realidad aumentada en turismo (Vishwakarma et al., 2020), sugiere que la aplicabilidad del TAM es limitada ya que solo toma en cuenta la adopción desde el punto de vista del usuario y no desde el del consumidor. Los autores propusieron para su estudio el *Modelo de Adopción basado en Valor* (Value-based Adoption Model: VAM) (Figura 12) para abordar este problema (Kim et al., 2007), considerando la adopción desde la perspectiva del consumidor.

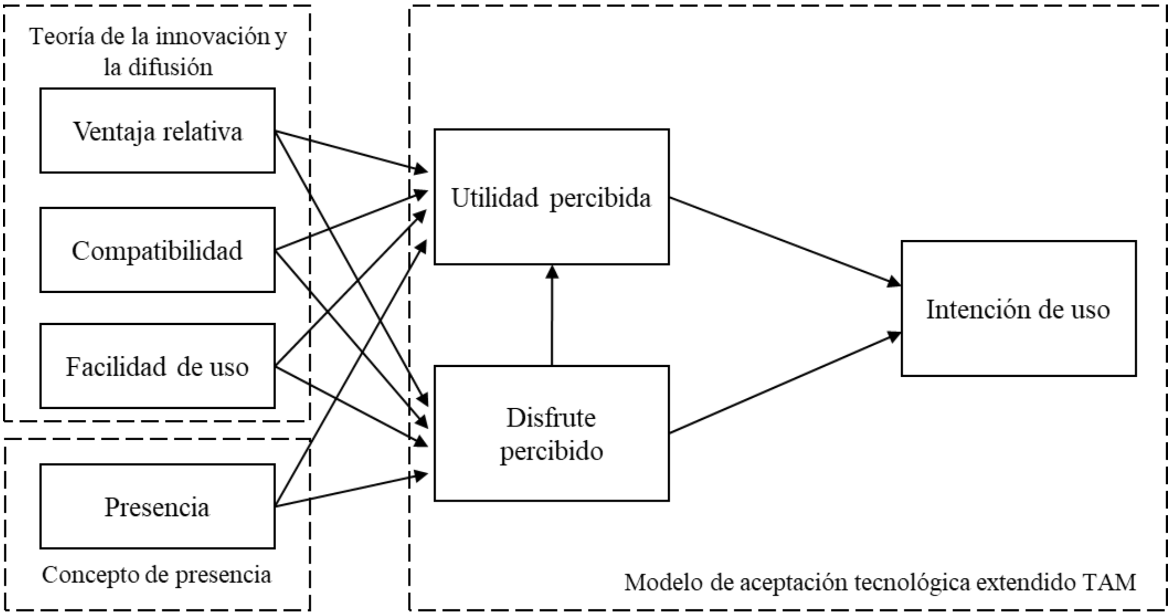

Figura 10: Modelo HE-TAM.

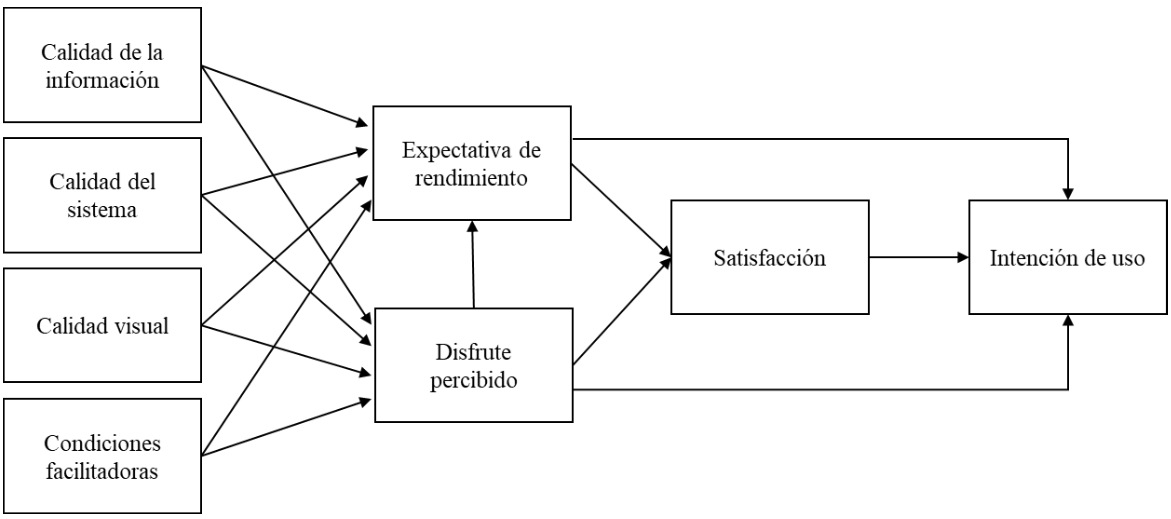

Figura 11: Modelo ART.

Sin embargo, se ha demostrado que las versiones ampliadas del TAM siguen siendo válidas en el ámbito educativo, donde las aplicaciones se utilizan para apoyar el proceso educativo y el aprendizaje autónomo. Esto se debe a que, en este ámbito, los estudiantes no son considerados consumidores, ya que las aplicaciones educativas no se comercializan. Prueba de lo anterior es que en los últimos años se ha aplicado TAM en diversos estudios del ámbito educacional, como por ejemplo en ciencias (Cabero-Almenara et al., 2019), geometría (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), comunicación digital (Al-Rahmi et al., 2020) y uso de software open source (Racero et al., 2020).

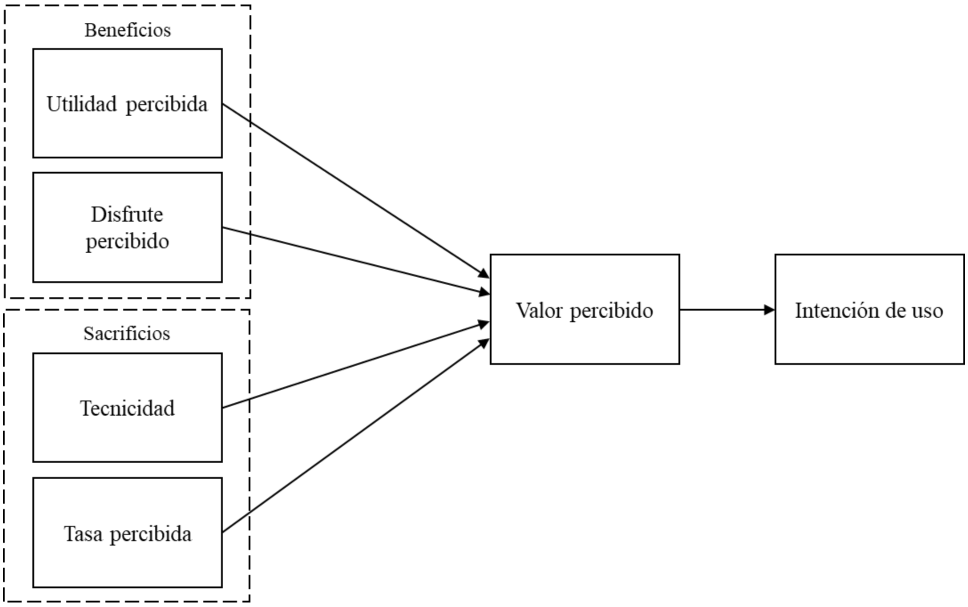

Figura 12: Modelo VAM.

En el campo de la educación en ingeniería, se ha encontrado un único estudio que ha abordado la aceptación de la tecnología de realidad aumentada. En este estudio, se utilizó el modelo TAM para investigar sobre las percepciones de los estudiantes en relación con la resolución de problemas en electromagnetismo (Ibáñez et al., 2016). Los resultados de la evaluación indicaron que la intención conductual de usar la tecnología de realidad aumentada estaba relacionada con el *disfrute percibido*. Sin embargo, se tuvo que excluir la variable de *utilidad percibida* debido a la falta de consistencia en las respuestas de los estudiantes. No se consideraron las características personales o ambientales de los estudiantes en este estudio.

Capítulo 3: Metodología

En el desarrollo de esta tesis doctoral, se utilizaron dos metodologías. La primera para la revisión sistemática del estado del arte, y la segunda para analizar los factores que influyen en la aceptación tecnológica de la realidad aumentada. A continuación, se detalla cada una de estas.

3.1 Metodología de la revisión sistemática

En esta parte del estudio **(P.I)** se adaptó y utilizó la metodología propuesta por Kitchenham (Kitchenham, 2004).

A. Preguntas de Investigación

Se plantearon las siguientes cinco preguntas de investigación sobre realidad aumentada en la educación en ingeniería:

RQ_{I-1}: ¿En qué asignaturas de ingeniería se ha usado realidad aumentada?

RQ_{I-2}: ¿En qué actividades educativas en ingeniería se han usado aplicaciones de realidad aumentada?

RQ_{I-3}: ¿Cómo se ha evaluado el impacto de las aplicaciones de realidad aumentada en la educación en ingeniería?

RQ_{I-4}: ¿Cuáles son las características técnicas principales de aplicaciones de realidad aumentada utilizadas en la educación en ingeniería?

RQ_{I-5}: ¿Qué grado de interactividad presentan las aplicaciones de realidad aumentada utilizadas en la educación en ingeniería?

B. Fuentes de Documentación

Para asegurar que se encontró la literatura relevante, se utilizaron cuatro bases de datos de investigación en línea representativas de la educación en ingeniería: 1) Web of Science; 2) Scopus; 3) Biblioteca Digital ACM; y 4) Biblioteca Digital IEEE Xplore. Un factor clave para seleccionar estas bases de datos fue su amplio soporte en actas de conferencias publicadas (Meho & Rogers, 2008).

C. Términos de Búsqueda

Se buscó la siguiente cadena de consulta: "*engineering education*" y "*augmented reality*". Se requería que apareciera en el título, resumen o palabras clave de cada publicación.

D. Selección de Estudios

Se adoptó un conjunto de criterios de inclusión y exclusión a partir de los criterios utilizados en algunas de las revisiones mencionadas anteriormente (Akçayır & Akçayır, 2017; Ibáñez & Delgado-Kloos, 2018), que se muestran en la Tabla 1.

Tabla 1: Criterios de inclusión y exclusión.

Criterios de inclusión	**Criterios de exclusión**
(a) Cualquier año de publicación. (b) Artículo de revista o de conferencia. (c) Informes de investigaciones empíricas. (d) Utilizado en la enseñanza de la ingeniería. (e) La realidad aumentada es el componente tecnológico principal.	(a) Cita el término "realidad aumentada" pero se trata de "realidad virtual". (b) Es utilizado para capacitación laboral. (c) Se enfatiza el diseño o desarrollo de aplicaciones en lugar del uso o evaluación educativa.

En la búsqueda inicial se encontraron 732 publicaciones. Se analizaron para descartar aquellas publicaciones duplicadas, lo que resultó en 583 publicaciones únicas. Después de eliminar las publicaciones que no estaban disponibles en texto completo, quedaron 523. Posteriormente, se aplicaron los criterios de inclusión y exclusión, quedando 56 publicaciones. Finalmente, se descartaron estudios que, teniendo los mismos autores, su foco del estudio era muy similar, por lo que el análisis final se centró en 52 publicaciones.

E. Metodología de Análisis

Cualquier deficiencia en el procedimiento de análisis puede reducir la validez o integridad de los resultados (DeFranco & Laplante, 2017). Por lo tanto, se analizaron cualitativamente los artículos seleccionados, considerando la relación entre contenido y contexto (Elo & Kyngäs, 2008; Hsieh & Shannon, 2005).

El proceso de análisis y clasificación tuvo como objetivo responder las cinco preguntas de investigación e involucró varias iteraciones. El proceso se detuvo cuando se alcanzó un consenso entre los autores. La principal fuente de desacuerdo entre los autores fue la insatisfacción con las categorías resultantes.

Para RQ_{I-1} (áreas de conocimiento), RQ_{I-2} (actividades educativas) y RQ_{I-5} (características de interacción), la categorización fue relativamente sencilla a partir de los estudios analizados.

Para RQ_{I-3} (evaluación del impacto), se identificaron dos cuestiones relevantes. La primera cuestión fue la identificación de los criterios educativos evaluados en las publicaciones. La segunda cuestión surgió a partir del hallazgo de que la mayoría de los estudios evaluaron la percepción subjetiva de los estudiantes o profesores con respecto a la tecnología de realidad aumentada. Aquí, se continuó el análisis para determinar las variables medidas en dichos estudios. Se analizaron los estudios sin categorías predefinidas a través de varias iteraciones (Glaser & Strauss, 2017). La identificación o definición de las variables medidas se basó en las descripciones de los estudios examinados. Una vez identificadas las variables, se analizó su correspondencia con cada uno de los estudios. En el caso del rendimiento académico, se realizó un análisis caso por caso de los resultados.

Para RQ_{I-4} (características de las aplicaciones), se realizó una búsqueda de clasificaciones relevantes que pudieran inspirar el análisis. Se identificaron dos clasificaciones informativas. La primera clasificación identificaba las tecnologías habilitadoras utilizadas en realidad aumentada (Wang et al., 2013). La segunda clasificación analizaba las características funcionales de las aplicaciones (Hugues et al., 2011).

3.2 Metodología del estudio de aceptación tecnológica

En esta parte del estudio, se utilizó una aplicación de realidad aumentada desarrollada especialmente para este efecto **(P.II)**, a la cual se le determinó su *intensión de uso* **(P.III)**.

A continuación, se señalan los procedimientos y muestras utilizadas y las técnicas de análisis de datos que se realizaron.

A. Procedimiento y Muestra

Para la evaluación en línea **(P.IV)**, se invitó por medio de correo electrónico a los estudiantes a que participaran. Se mostró un video de tres minutos explicando el uso de la aplicación. Posteriormente, se compartieron enlaces para que los estudiantes descargaran la aplicación desde Google Play (para sistemas Android) y APP Store (para sistemas IOS). Los estudiantes pudieron utilizar la aplicación libremente. A continuación, se les pidió que completaran la encuesta. La muestra para este caso estaba compuesta por 173 estudiantes.

La evaluación presencial **(P.V)** se realizó en una sesión guiada con los estudiantes. La experiencia y la encuesta se llevaron a cabo en un laboratorio implementado con tablets. Al principio, se mostró un video de 3 minutos que demostraba cómo funcionaba la aplicación interactiva de realidad aumentada. Luego, los estudiantes experimentaron interactuando con la aplicación durante 30 minutos, realizando varios ejercicios guiados, de forma similar a otros estudios sobre la aceptación de esta tecnología en educación (Ibáñez et al., 2016; Miranda Bojórquez et al., 2016; Wojciechowski & Cellary, 2013) y en otros campos (Pantano et al., 2017; Voinea et al., 2020). Los estudiantes analizaron diferentes tipos de comportamientos de intensidad de corriente mientras practicaban con circuitos en serie o en paralelo y modificaban los valores de voltaje y resistencia. Además, los estudiantes pudieron interactuar con la aplicación libremente. Al final de la experiencia, se llevó a cabo la encuesta. La muestra estuvo compuesta en esta oportunidad por 190 estudiantes.

Para ambos estudios se utilizó el método de muestreo por conveniencia, una técnica de muestreo no probabilístico que implica seleccionar la muestra de una población que es fácil de alcanzar o contactar. Este tipo de muestreo es útil para las pruebas piloto. La participación de los estudiantes fue voluntaria, no asociada a la evaluación y no se ofrecieron puntos extra para participar en el estudio. Además, se garantizó el anonimato y la estricta confidencialidad de los datos. Anteriormente, se han utilizado pruebas piloto como las realizadas en el desarrollo de esta tesis para determinar la intención de comportamiento en aplicaciones de realidad aumentada (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. Análisis de Datos

Se realizaron pruebas simultáneas a los modelos y las hipótesis propuestas **(P.IV** y **P.V)**, aplicando ecuaciones estructurales mediante el método de mínimos cuadrados parciales (Partial Least Squares: PLS), utilizando el software Smart PLS 3.2.9 © (Ringle et al., 2015).

Se adoptó la técnica PLS debido a que permite combinar variables no observadas que representan conceptos teóricos y datos de mediciones, que se utilizan para proporcionar evidencia sobre las relaciones entre variables latentes (Williams et al., 2009). Este método es apropiado ya que la aproximación incluye modelos complejos y variables compuestas (Sarstedt et al., 2016).

La aplicación de la técnica PLS consiste en diferentes pasos, siendo el primero el ajuste del modelo (Barclay et al., 1995). La prueba de ajuste se realiza para el modelo estimado aplicando un proceso de remuestreo de 5.000 submuestras (Henseler et al., 2016). En segundo lugar, se evalúa el modelo de medición y, en tercer lugar, se analiza el ajuste del modelo (Müller et al., 2018). Se consideraron variables compuestas de Tipo B para este modelo (Cepeda-Carrion et al., 2019).

Se realizó una revisión de la literatura para determinar las encuestas para ambos estudios. Se utilizaron cuestionarios de estudios anteriores, ya que estas preguntas habían sido validadas previamente.

Para la investigación correspondiente a la determinación de la aceptación tecnológica mediante una evaluación en línea **(P.IV)**, se empleó una encuesta que constaba de 15 preguntas para la recopilación de datos. La Tabla 2 presenta los estudios utilizados para adaptar los constructos (o variable latente, que son conceptos no observables ni medibles directamente) e indicadores (o variable observada, que son las variables que se miden en los sujetos de estudio, mediante afirmaciones o preguntas valoradas en una escala de Likert).

Para la investigación correspondiente a la determinación de la aceptación tecnológica mediante una evaluación presencial **(P.V)**, se utilizaron los constructos e indicadores del estudio anterior, y se agregaron 7 indicadores correspondientes a los constructos de *Facilidad de uso* y *Utilidad percibida* (ver Tabla 3).

Tabla 2: Estudios e indicadores utilizados en evaluación en línea.

Constructo	Estudio	Indicador
Normas subjetivas	(Teo et al., 2008)	Las personas cuyas opiniones valoro, me animan a utilizar las nuevas tecnologías. Las personas que son importantes para mí me ayudan a utilizar las nuevas tecnologías.
Optimismo tecnológico	(Chung et al., 2015)	Los productos y servicios que utilizan las nuevas tecnologías son mucho más cómodos de usar. Prefiero utilizar la tecnología más avanzada disponible. La tecnología hace que mi trabajo sea más eficiente.
Innovación tecnológica	(Chang et al., 2017)	Si me entero de que hay nuevas tecnologías, busco la manera de probarlas. Entre mis compañeros, suelo ser el primero en probar las nuevas tecnologías. Me gusta experimentar con las nuevas tecnologías.
Actitud hacia el uso	(Pantano et al., 2017)	Creo que utilizar la aplicación en clase sería positivo. La aplicación es tan interesante que quieres aprender más sobre ella. Tiene sentido utilizar la aplicación para el estudio de circuitos eléctricos. La aplicación es una buena idea.
Intención de uso	(Balog & Pribeanu, 2010)	Me gustaría tener esta aplicación si tuviera que estudiar circuitos eléctricos. Me gustaría utilizar esta aplicación para aprender sobre circuitos eléctricos. Recomendaría a otros estudiantes que utilizaran esta aplicación para estudiar circuitos eléctricos.

Tabla 3: Estudios e indicadores incorporados para la evaluación presencial.

Constructo	Estudio	Indicador
Facilidad de uso	(Pantano et al., 2017)	La aplicación es muy fácil de usar. La aplicación es intuitiva. Fue fácil aprender a utilizar la aplicación. El manejo de la aplicación ha sido sencillo.
Utilidad percibida	(Wojciechowski & Cellary, 2013)	El uso de la aplicación mejora el aprendizaje en el aula. El uso de la aplicación durante las clases facilitaría la comprensión de ciertos conceptos. Creo que la aplicación es útil para el aprendizaje.

Capítulo 4: Resultados y discusión

Este capítulo presenta un resumen de los resultados obtenidos en las publicaciones **P.I – P.V** para alcanzar los objetivos propuestos en el apartado 1.2. Para más detalle, se sugiere revisar en extenso, las publicaciones realizadas por esta tesis por compendio.

4.1 Revisión sistemática del uso de realidad aumentada en educación en ingeniería

A continuación, se abordará de forma estructurada, las respuestas a cada una de las preguntas de investigación presentadas en el primer estudio **(P.I.)**.

RQ_{I-1}: ¿En qué asignaturas de ingeniería se ha usado realidad aumentada?

La tecnología de realidad aumentada ha sido aplicada con mayor frecuencia en dibujo técnico y electrónica. En dibujo técnico, así como en construcción y topografía, se muestran visualizaciones en 3D de elementos para mejorar su comprensión. En electrónica, se ha encontrado más diversidad al modelar componentes electrónicos con algún nivel de interacción. El uso de esta tecnología apenas se ha extendido a otras áreas de la educación en ingeniería. El uso de esta tecnología es heterogéneo en las diferentes áreas en que se divide este campo. Una pregunta abierta es si esta situación se debe a la adecuación diferente de la realidad aumentada a las necesidades educativas de diferentes áreas o simplemente a la falta de interés en estas. La ausencia de esta tecnología en áreas de ingeniería como informática o telecomunicaciones, puede ser un argumento para la primera hipótesis. De hecho, disciplinas cuya naturaleza es virtual, no necesitan utilizar la tecnología de realidad aumentada porque ya utilizan una gran cantidad de recursos y materiales virtuales en dispositivos digitales –por ejemplo, visualización de software para programación o algoritmos (Naps et al., 2003; Stasko et al., 1988)–.

En la literatura revisada, la tecnología de realidad aumentada es utilizada para explicar conceptos y habilidades básicas. Aunque esta tecnología podría potencialmente apoyar el desarrollo de habilidades avanzadas que en el futuro serán demandadas en la industria 4.0, en el presente, este no es caso. Por lo tanto, existe un nicho para más aplicaciones de realidad aumentada en el futuro. Los sectores que podrían beneficiarse son los automotriz, mecánico, automatización y aeroespacial.

$RQ_{I\text{-}2}$: ¿En qué actividades educativas en ingeniería se han usado aplicaciones de realidad aumentada?

Las actividades educativas en que se usan aplicaciones de realidad aumentada varían con la materia. Se han utilizado principalmente en laboratorios de electrónica para interactuar con circuitos eléctricos y en clases de dibujo técnico para resolver problemas con la visualización interactiva en 3D. En clases de construcción, se utilizan para proporcionar información complementaria, como notas, imágenes y videos. Sin embargo, su uso sigue siendo minoritario incluso en estas áreas, y se necesitan más aplicaciones diseñadas, implementadas y evaluadas para adecuarse a cada área.

Para mejorar su uso en la educación, se deben integrar las aplicaciones de realidad aumentada con métodos de aprendizaje activo, especialmente en actividades de laboratorio, lo que puede fomentar el aprendizaje colaborativo y permitir la personalización de ejercicios. Además, se debe integrar estas aplicaciones con sistemas centralizados de gestión de aprendizaje para proporcionar retroalimentación en tiempo real sobre el rendimiento de los estudiantes y realizar un seguimiento de sus actividades y dificultades individuales.

La virtualización de actividades a gran escala, como los laboratorios virtuales, puede ser útil en la educación, pero requiere la planificación cuidadosa de la participación del profesorado y la adopción de modelos pedagógicos centrados en el estudiante. En resumen, se necesitan más investigaciones para mejorar la integración de la realidad aumentada en educación y adaptarse a las necesidades de cada área.

$RQ_{I\text{-}3}$: ¿Cómo se ha evaluado el impacto de aplicaciones de realidad aumentada en la educación en ingeniería?

Se ha evaluado la percepción de los estudiantes y profesores, así como el rendimiento académico de los estudiantes mediante las siguientes metodologías: realizando comparaciones entre grupo experimental y de control; utilizando pruebas antes y después del experimento; una única evaluación al final del mismo; comparando las calificaciones obtenidas en el año académico actual con las obtenidas en años anteriores; y evaluando el rendimiento en diferentes entornos educativos, tales como laboratorios físicos, de realidad virtual y de realidad aumentada.

En general, se ha observado que la tecnología de realidad aumentada acrecienta el interés y la motivación de los estudiantes y promueve una participación activa en situaciones de aprendizaje. Los estudiantes encuentran útiles las aplicaciones para mejorar su rendimiento académico y realizar trabajos autónomos. Sin embargo, consideran necesario que se les explique la teoría antes de usar las aplicaciones de manera autónoma. Los profesores creen que sería útil que los estudiantes la usen desde el comienzo de la asignatura para aprender nuevos conceptos.

Los estudiantes han informado problemas técnicos en las aplicaciones, como poca estabilidad, parpadeo y retraso, que podrían ser debidos a lo novel de la tecnología o a prototipos insuficientemente elaborados.

Para evaluar variables, como la facilidad de uso, la motivación y la aceptación de la tecnología, se necesitan instrumentos de evaluación más elaborados, no solo encuestas subjetivas. La percepción en diferentes aspectos ha sido evaluada con mayor frecuencia para los estudiantes que para los profesores. Se recomienda realizar más estudios en los profesores ya que son agentes clave en la adopción de tecnologías educativas.

En cuanto al impacto en el rendimiento académico, la habilidad espacial es la variable más comúnmente medida y la realidad aumentada ha mostrado un impacto positivo. Sin embargo, se necesitan más evaluaciones controladas para obtener resultados más representativos y generalizables. También es necesario evaluar la tecnología de realidad aumentada en más materias y enfoques educativos.

$RQ_{I\text{-}4}$: ¿Cuáles son las características técnicas principales de las aplicaciones de realidad aumentada utilizadas en la educación en ingeniería?

Las características de las aplicaciones fueron analizadas mediante dos clasificaciones. La primera clasificación identifica cinco tecnologías habilitadoras (Wang et al., 2013): representación visual; dispositivo computacional; medios de entrada; servicio de visualización; y sistema de seguimiento. La representación visual más común son las figuras en 3D. La mayoría de las aplicaciones se ejecutan en computadoras de escritorio o portátiles, aunque su uso en dispositivos móviles está creciendo. La mayoría de las aplicaciones de realidad aumentada utilizan simultáneamente pantallas basadas en monitores, seguimiento basado en marcadores y movimiento de los dispositivos como medios de entrada.

La segunda clasificación identifica cinco características funcionales (Hugues et al., 2011): visibilidad aumentada; asociación perceptiva con la incrustación de objetos virtuales; realidad documentada; virtualidad documentada; y entendimiento aumentado. La característica funcional más utilizada es la visibilidad aumentada, utilizando elementos 3D para apoyar el entrenamiento de habilidades espaciales. En el futuro, se podrían mejorar las aplicaciones de realidad aumentada mediante la incorporación de características funcionales de asociación perceptiva y la integración de objetos virtuales para obtener elementos virtuales que interactúen de manera más natural con el entorno. También se debería explorar más los sistemas de seguimiento sin marcadores para lograr una interacción más fluida con el entorno sin necesidad de estos.

$RQ_{I\text{-}5}$: ¿Qué grado de interactividad presentan las aplicaciones de realidad aumentada utilizadas en la educación en ingeniería?

Solo alrededor de una cuarta parte de las aplicaciones utilizadas en los estudios tienen cierto grado de interactividad, logrando solamente en algunos casos el nivel III (interacción compleja, el estudiante puede manipular objetos para analizar su comportamiento) de un total de cuatro niveles (Aqel, 2013) y la personalización de la experiencia de aprendizaje es mínima. Por lo tanto, se necesitan más esfuerzos para desarrollar aplicaciones que permitan niveles más altos de interactividad. Esto permitiría actividades educativas más enriquecedoras y permitiría a los estudiantes tener un papel más activo en su aprendizaje.

4.2 Diseño de una aplicación de realidad aumentada

Se desarrolló una aplicación de realidad aumentada para analizar la corriente continua (DC) en circuitos resistivos **(P.II)**. El grado de interactividad de las aplicaciones existentes en esta materia no es alto (nivel III) debido a que solo pueden manipular objetos gráficos para analizar su comportamiento (Matcha & Rambli, 2012; Restivo et al., 2014). Por lo tanto, nuestro propósito fue crear una aplicación con un nivel de interactividad más alto, con interacción en tiempo real, generando una simulación en la que los estímulos generan respuestas complejas (nivel IV) (Aqel, 2013).

La aplicación desarrollada ofrece cinco tipos de circuitos en serie y paralelo para elegir. Baterías, bombillas y resistencias se pueden incorporar al circuito. Los circuitos de la aplicación permiten cualquier configuración y simulan el flujo de corriente cada vez que se incorporan baterías, bombillas y resistencias. Los usuarios pueden cambiar los valores de voltaje de baterías y la resistencia en bombillas y resistencias. La aplicación calcula en tiempo real y muestra el voltaje y amperaje resultante (Figura 13).

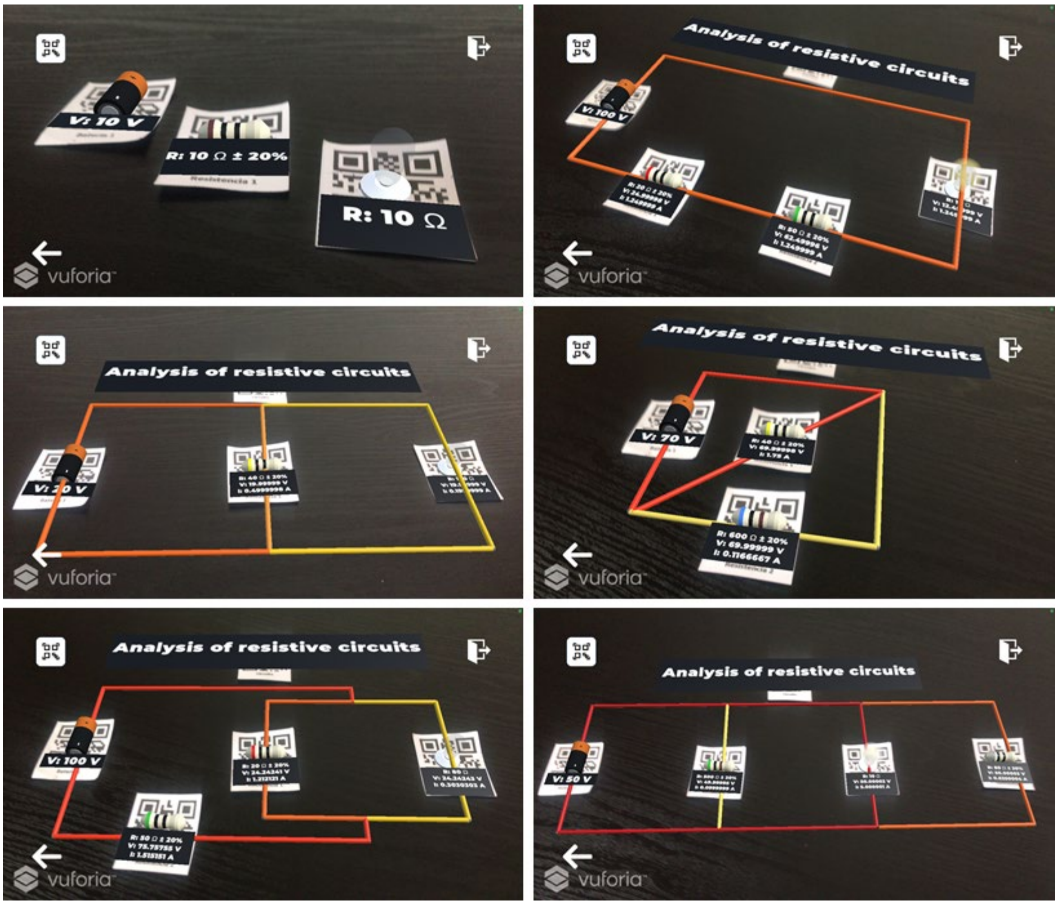

Figura 13: Aplicación interactiva desarrollada.

La aplicación asigna un color según el valor de amperaje en cada rama del circuito. Una rama roja indica un alto amperaje, naranja indica un amperaje medio, amarillo indica un amperaje bajo y gris indica ningún amperaje. La intensidad de la luz de la bombilla depende del amperaje de la rama en la que se encuentra.

Utilizando el método de bucle y aplicando la ley de voltaje de Kirchhoff (Floyd, 2007), la aplicación calcula los valores de intensidad de corriente y voltajes. La aplicación utiliza un rastreador óptico en su funcionamiento. El circuito, las baterías, las bombillas y las resistencias utilizan un código QR como objetivo para posicionar cada figura en realidad aumentada en el espacio. La aplicación se desarrolló en Unity 3D, utilizando el SDK de Vuforia. Los objetos tridimensionales se crearon con Blender (Figura 14).

Así, la aplicación desarrollada permite a los estudiantes practicar con una amplia gama de configuraciones de circuitos eléctricos debido a su alto nivel de interactividad. Además de tener varios tipos de circuitos en serie y paralelo para practicar, los estudiantes pueden configurarlos libremente para comprender el comportamiento de la corriente a través de las ramas. Al interactuar libremente con la aplicación, los estudiantes pueden comprender mejor cómo funciona la electricidad. Además, les proporciona a los estudiantes una herramienta que entrega los valores resultantes si desean desarrollar ejercicios numéricos.

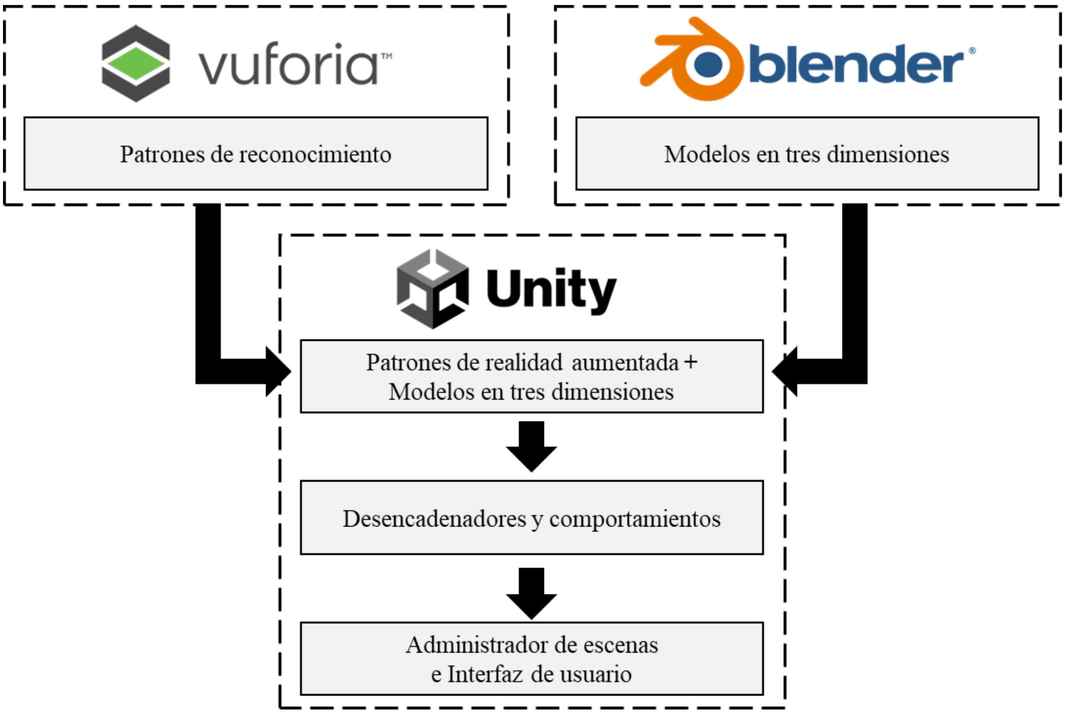

Figura 14: Arquitectura de aplicación desarrollada.

A continuación, se evaluó la *actitud hacia el uso* e *intención de uso* que demostraron los estudiantes hacia la aplicación desarrollada **(P.III)**, debido a que estas variables deberían ser suficientes para predecir el comportamiento de los usuarios (Ajzen, 1991). Se aplicó una encuesta a 314 estudiantes que cursaban diferentes especialidades de ingeniería. Los resultados demostraron que los estudiantes presentaron un alto nivel en ambas variables: *actitud hacia el uso* con 4,41 e *intención de uso* con 4,36. Ambos valores pueden oscilar entre un valor mínimo de 1 y un máximo de 5.

4.3 El rol del optimismo y la innovación tecnológica en la aceptación de la tecnología de realidad aumentada en educación en ingeniería

Los resultados obtenidos para el modelo evaluado en línea **(P.IV)** se muestran en la Figura 15 y la Tabla 4. En esta tabla también se muestran los coeficientes path (o coeficientes de trayectoria, que denotan la influencia que tiene un constructo sobre otro) obtenidos por cada una de las hipótesis. Todas las hipótesis del modelo fueron aceptadas.

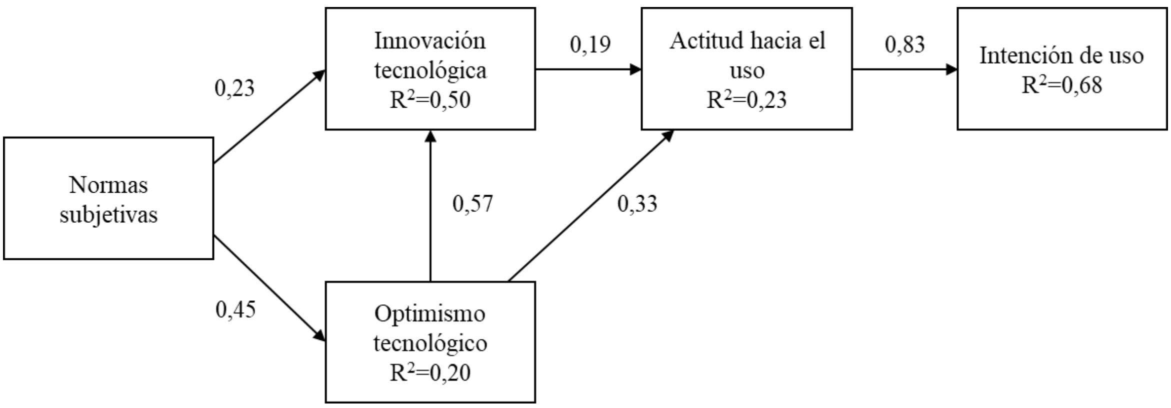

Figura 15: Modelo de investigación resultante de la evaluación en línea.

El *optimismo tecnológico* depende en un rango menor de *normas subjetivas* ($R^2 = 0,20$) (H_{IV-1}), probablemente debido a la falta de otros factores. Sin embargo, este valor no es tan pequeño, ya que está explicado por una sola variable. Además, las *normas subjetivas* tienen un gran efecto en el *optimismo tecnológico* (0,45). Se puede inferir que, si los estudiantes viven en un entorno donde hay una opinión positiva sobre el uso de la tecnología, percibirán las nuevas tecnologías como herramientas que facilitan su educación. Por lo tanto, si las instituciones de educación superior resaltan las virtudes del uso de la tecnología en el proceso educativo, podrían generar una opinión favorable entre los estudiantes sobre las ventajas de incorporarlas.

Tabla 4: Resultados del modelo estructural de la evaluación en línea.

Hipótesis	**Path**	**p-value**	**Soportada**
H_{IV-1}: Normas subjetivas → Optimismo tecnológico	0,45	0,00	Sí
H_{IV-2}: Normas subjetivas → Innovación tecnológica	0,23	0,00	Sí
H_{IV-3}: Optimismo tecnológico → Innovación tecnológica	0,57	0,00	Sí
H_{IV-4}: Optimismo tecnológico → Actitud hacia el uso	0,33	0,00	Sí
H_{IV-5}: Innovación tecnológica → Actitud hacia el uso	0,19	0,02	Sí
H_{IV-6}: Actitud hacia el uso → Intención de uso	0,83	0,00	Sí

Las *normas subjetivas* y el *optimismo tecnológico* tienen un impacto relevante en la *innovación tecnológica* ($R^2 = 0,50$) (H_{IV-2} y H_{IV-3}). El efecto directo de las *normas subjetivas* en la *innovación tecnológica* es de 0,23, mientras que la influencia directa del *optimismo tecnológico* es de 0,57. Además, se puede observar que el *optimismo tecnológico* tiene una mediación complementaria estadísticamente significativa entre las *normas subjetivas* y la *innovación tecnológica*.

El impacto indirecto de las *normas subjetivas* en la *innovación tecnológica* a través del *optimismo tecnológico* es de 0,26 (0,45*0,57). Esto indica que gran parte de los efectos de las *normas subjetivas* en la *innovación tecnológica* se explican por el *optimismo tecnológico*. Esto significaría que el estatus de pionero de los estudiantes en el uso de una tecnología se asocia con su percepción positiva de la utilidad de la tecnología. Además, la percepción en los círculos académicos de los estudiantes influye en su disposición para usarla. La *actitud hacia el uso* depende en un grado medio ($R^2 = 0,23$) del *optimismo tecnológico* y la *innovación tecnológica* (H_{IV-4} y H_{IV-5}). Esto se debe a la ausencia de variables no incluidas en el análisis, como la percepción de la *facilidad de uso* y *la utilidad percibida*. No obstante, estas características personales (*optimismo tecnológico* e *innovación tecnológica*) explicarían moderadamente la actitud de los estudiantes hacia el uso.

El efecto directo del *optimismo tecnológico* en la *actitud hacia el uso* es de 0,33, mientras que el impacto directo de la *innovación tecnológica* es de 0,19. Esto es consistente con estudios anteriores en otras áreas, que indican que la actitud hacia el uso es influenciada por el optimismo tecnológico (Kros et al., 2011; Theotokis et al., 2008) y la innovación tecnológica (Al-Ajam & Md Nor, 2015; Kros et al., 2011; J. C. Lin & Chang, 2011).

Además, existe una mediación complementaria estadísticamente significativa de la *innovación tecnológica*, entre el *optimismo tecnológico* y la *actitud hacia el uso*. El efecto indirecto es de 0,11 (0,57*0,19), lo que indica que solo una parte del impacto del *optimismo tecnológico* y la *actitud hacia el uso* puede ser explicado por la mediación con la *innovación tecnológica*. Se puede inferir que no es suficiente que los estudiantes sean pioneros en el uso de tecnologías para tener una actitud positiva hacia la adopción de tecnologías; es imperativo que perciban estas tecnologías como útiles. Además, su actitud hacia el uso de tecnologías puede ser influenciada por la percepción de estas tecnologías en sus respectivos círculos académicos.

Por último, el modelo muestra que la intención conductual de uso depende fuertemente de la actitud hacia el uso (R^2 = 0,68) ($H_{IV\text{-}6}$), lo que indica que un estudiante con una actitud positiva hacia el uso de la tecnología tendría la intención de usarla, lo que en última instancia indica el uso efectivo de la tecnología en el aula. Esto es consistente con estudios anteriores de realidad aumentada en otras áreas, que muestran que *la intención de uso* está fuertemente explicada por la *actitud hacia el uso* (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 Aceptación tecnológica de una aplicación interactiva de realidad aumentada sobre circuitos resistivos para estudiantes de ingeniería

Los resultados obtenidos para el modelo evaluado en forma presencial **(P.V)** se muestran en la Tabla 5 y Figura 16 (flechas discontinuas muestran trayectorias no significativas). Ocho de las diez hipótesis del modelo fueron aceptadas.

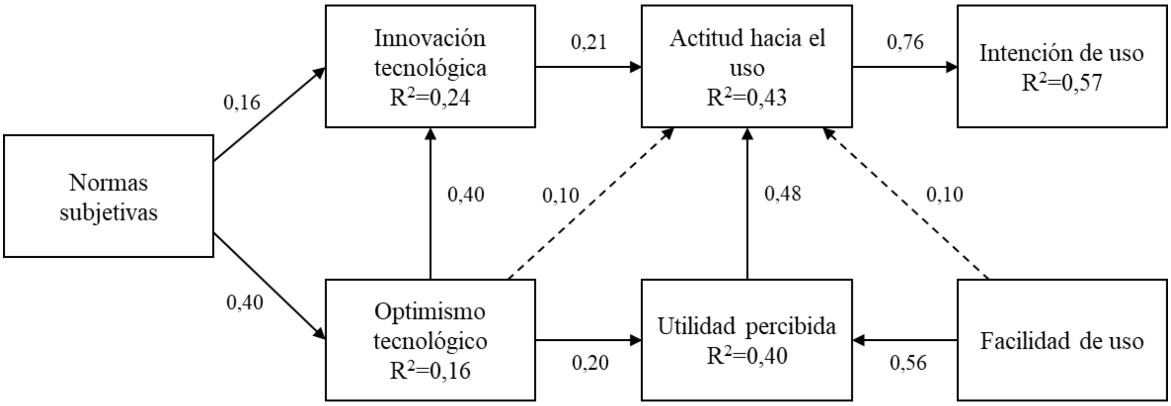

Figura 16: Modelo de investigación resultante de la evaluación presencial.

Tabla 5: Resultados del modelo estructural de la evaluación presencial.

Hipótesis	Path	p-value	Soportada
H_{V-1}: Normas subjetivas → Optimismo tecnológico	0,40	0,00	Sí
H_{V-2}: Normas subjetivas → Innovación tecnológica	0,16	0,02	Sí
H_{V-3}: Optimismo tecnológico → Innovación tecnológica	0,40	0,00	Sí
H_{V-4}: Optimismo tecnológico → Utilidad percibida	0,20	0,01	Sí
H_{V-5}: Optimismo tecnológico → Actitud hacia el uso	0,10	0,14	No
H_{V-6}: Innovación tecnológica → Actitud hacia el uso	0,21	0,00	Sí
H_{V-7}: Facilidad de uso → Utilidad percibida	0,56	0,00	Sí
H_{V-8}: Facilidad de uso → Actitud hacia el uso	0,10	0,14	No
H_{V-9}: Utilidad percibida → Actitud hacia el uso	0,48	0,00	Sí
H_{V-10}: Actitud hacia el uso → Intención de uso	0,76	0,00	Sí

El *optimismo tecnológico* de los estudiantes depende de un pequeño rango de *normas subjetivas* (R^2 = 0,16) (H_{V-1}). Esto indica que existen otros factores que ayudan a explicar mejor este factor. La *innovación tecnológica* depende moderadamente de las *normas subjetivas* y del *optimismo tecnológico* (R^2 = 0,24) (H_{V-2} y H_{V-3}). El *optimismo tecnológico* tiene una mediación complementaria estadísticamente significativa entre las *normas subjetivas* y la *innovación tecnológica*. El efecto directo de las *normas subjetivas* en la *innovación tecnológica* es de 0,16, mientras que el efecto indirecto debido al *optimismo tecnológico* es de 0,16 (0,40*0,40). Esto implica que el *optimismo tecnológico* explica la mitad del impacto que las *normas subjetivas* tienen en la *innovación tecnológica*. Estos hallazgos son concordantes con los obtenidos en la evaluación en línea.

La *utilidad percibida* depende del *optimismo tecnológico* y de la *facilidad de uso* (R^2 = 0,40) (H_{V-4} y H_{V-7}). Sin embargo, la *facilidad de uso* (0,56) tiene un impacto más significativo que el *optimismo tecnológico* (0,20), lo que indica que los estudiantes relacionan el nivel de *facilidad en el uso* de una aplicación, como una fortaleza para lograr un aprendizaje más significativo.

La *actitud hacia el uso* depende de la *utilidad percibida* y la *innovación tecnológica* (R^2 = 0,43) (H_{V-6} y H_{V-9}). La *utilidad percibida* (0,48) tiene un mayor impacto que la *innovación tecnológica* (0,21), lo que implica que los estudiantes deben tener claro la utilidad de la aplicación para sus estudios y estar dispuestos a usarla. Sin embargo, el *optimismo tecnológico* y la *facilidad de uso* no tienen un impacto estadísticamente significativo en la *actitud hacia el uso* (H_{V-5} y H_{V-8}).

El *optimismo tecnológico* tiene un efecto indirecto en la *actitud hacia el uso*, que es causado por la moderación de la *innovación tecnológica* (0,40* 0,21 = 0,08) y *la utilidad percibida* (0,20*0,48 = 0,10), aunque ambos efectos son insignificantes.

Aunque la *facilidad de uso* no tiene un efecto estadísticamente significativo en *la actitud hacia el uso*, se produce una mediación completa por la *utilidad percibida* (0,56*0,48 = 0,27), lo que significa que la aplicación no solo debe ser fácil de usar, sino que también debe ser útil para los estudiantes en mejorar su rendimiento académico.

Finalmente, los resultados muestran que la *intención de uso* depende fuertemente de la *actitud hacia el uso* (R^2 = 0,57) (H_{V-10}).

4.5 Implicancias teóricas

Este estudio tiene importantes implicancias teóricas en varias dimensiones. En primera instancia, la revisión sistemática **(P.I)** identifica fortalezas y debilidades de la tecnología de realidad aumentada en educación en ingeniería, identificando las áreas de ingeniería donde se requiere más investigación y proporciona sugerencias a investigadores y desarrolladores de aplicaciones para mejorar la eficacia de las metodologías existentes.

Esta investigación resalta la necesidad de que más aplicaciones de realidad aumentada apoyen habilidades avanzadas que son demandadas por la industria 4.0 y sugiere que estas aplicaciones deban permitir la personalización de ejercicios y su integración en sistemas centralizados de gestión de aprendizaje para proporcionar así información en tiempo real sobre los rendimientos de los estudiantes.

Además, los hallazgos indican que la virtualización a gran escala de actividades educativas, a través de laboratorios virtuales tienen un gran potencial, pero plantea desafíos educativos que requieren modelos pedagógicos adecuados. Es decir, deben coordinarse la educación y las nuevas tecnologías, lo que requiere una revisión y actualización de los modelos pedagógicos existentes.

Otro hallazgo importante es la falta de estudios para evaluar la usabilidad en aplicaciones de realidad aumentada, utilizando enfoques estándar como SUS o la ISO 9241-11. Lo anterior destaca la necesidad de investigar y establecer estándares para la evaluación de la usabilidad en aplicaciones de realidad aumentada, lo que podría tener importantes implicancias en la teoría de la usabilidad y diseño de interfaces de usuario.

Para finalizar, los resultados de este estudio sugieren que los diseñadores deberían estudiar la incorporación de las características funcionales de asociación perceptiva con la incrustación de objetos virtuales para obtener así, elementos virtuales que interactúen de manera más natural con el entorno. Este hallazgo podría tener importantes implicancias sobre las teorías de la percepción y la cognición, ya que destaca la importancia de la integración natural de los elementos virtuales en el entorno para una experiencia de usuario óptima.

En cuanto a la parte de la investigación empírica, se han propuesto y validado dos modelos, los que determinan el papel que juegan el *optimismo* y la *innovación tecnológica* en la aceptación de la tecnología de realidad aumentada, así como la influencia de su entorno directo con las *normas subjetivas*.

El primer estudio empírico **(P.IV)** analiza la influencia de estos factores directamente en la *actitud hacia el uso* y la *intensión de uso* por parte de estudiantes de ingeniería. Debido a la naturaleza de los constructos analizados y para realizar la comparación con la siguiente fase, la recolección de información para este estudio se realizó en línea.

El segundo estudio empírico **(P.V)** propuso un modelo extendido del TAM para explorar factores que pueden influir en la *intención de uso* de una aplicación de realidad aumentada, incorporando es esta oportunidad los constructos de *facilidad de us*o y de *utilidad percibida*. Debido a la naturaleza de estos dos últimos constructos, la recolección de información se realizó de forma presencial.

Muchos estudios han investigado la adopción tecnológica de realidad aumentada. Sin embargo, pocos han considerado el campo educativo, más específicamente, la ingeniería.

Además, pocos estudios han enfatizado las características de los estudiantes, como el *optimismo tecnológico* y la *innovación tecnológica*, que son especialmente importantes porque los estudiantes son ahora nativos digitales. La inclusión de *normas subjetivas* también se vuelve relevante para determinar si influyen en las características evaluadas de los estudiantes y, eventualmente, en la adopción de esta tecnología. Como estos son factores independientes de la tecnología que se está evaluando, los resultados pueden tener una implicación importante en la adopción de otras tecnologías.

Por lo tanto, los dos modelos presentados incorporan factores no estudiados en este contexto. Los resultados de esta tesis proporcionan información adicional sobre la aceptación de la tecnología de realidad aumentada, identificando factores externos a la tecnología y específicos de los usuarios. Particularmente en este caso, elementos del entorno académico del estudiante (profesores, compañeros de clase, familia, directivos de los establecimientos educacionales y medios de comunicación) pueden afectar a la disposición o creencias del estudiante sobre las tecnologías, lo que puede impactar en su aceptación de una tecnología en particular.

Por lo tanto, estos hallazgos nos ayudan a comprender las motivaciones y fundamentos que los estudiantes universitarios de ingeniería tienen para adoptar la tecnología de realidad aumentada en el entorno académico. Finalmente, en el caso del segundo estudio empírico **(P.V)** los resultados muestran que el TAM sigue siendo válido y con un nivel predictivo satisfactorio cuando se evalúa en un contexto educativo. Sin embargo, un estudio que use una aplicación con un diseño deficiente (por ejemplo, menos interactividad, estética) podría no llegar a las mismas conclusiones.

4.6 Implicancias prácticas

En primer lugar, el estudio de revisión sistemática **(P.I)** puede ser útil para educadores, desarrolladores e investigadores para mejorar las aplicaciones de realidad aumentada y su uso educativo de diferentes maneras. Los educadores interesados en la realidad aumentada pueden conocer diferentes aspectos de las aplicaciones, lo que puede ser útil para la toma de decisiones, desde sus usos educativos hasta cuestiones técnicas, como la evaluación de su impacto en los estudiantes.

En segundo lugar, se desarrolló una aplicación de realidad aumentada para el análisis de circuitos resistivos **(P.II)**. Esta aplicación puede utilizarse en clases teóricas para que los académicos enseñen conceptos y comportamientos de circuitos eléctricos. También puede utilizarse en laboratorios, donde los estudiantes practiquen conceptos aprendidos. Esta aplicación produjo una alta *actitud hacia el uso* e *intención de uso* por parte de los estudiantes **(P.III)**.

Con respecto a los modelos de aceptación propuestos (**P.IV** y **P.V**), los hallazgos demuestran que aspectos personales (la creencia de que las tecnologías en general son elementos facilitadores de distintas tareas, y ser proclive a ser pionero en el uso de nuevas tecnologías) y ambientales (la importancia que los estudiantes le entregan a las opiniones de su entorno académico, explicado anteriormente) influyen en la disposición a utilizar la aplicación. Esto implica que las instituciones de educación superior pueden influir en sus estudiantes para adoptar nuevas tecnologías y convencerlos de que su uso ayudará a mejorar su rendimiento académico. Esto podría lograrse mediante la difusión de los resultados alentadores debido a la inclusión de esta tecnología en la educación.

En cuando al modelo TAM extendido (**P.V**), la *facilidad de uso* de la aplicación influye en la percepción que los estudiantes tienen sobre su *utilidad*. Por lo tanto, debe considerarse este aspecto al desarrollar aplicaciones en esta área. Sin embargo, la disposición de los estudiantes a utilizar esta tecnología depende de cuántos estudiantes creen que pueden mejorar su rendimiento académico mediante su uso y no de lo fácil que creen que es utilizar la aplicación. Esto es coherente con otros hallazgos que utilizaron una aplicación en la educación científica (Arvanitis et al., 2011) o de la química (Wojciechowski & Cellary, 2013). Sin embargo, estos hallazgos difieren de otras áreas como el turismo (Chung et al., 2015; Lee et al., 2017), donde la *actitud hacia el uso* está influida por la *facilidad de uso* y no por la *utilidad percibida*. Esto es lógico porque, cuando una persona utiliza una aplicación para estudiar, espera que tenga un impacto positivo en los resultados académicos. En cambio, cuando esa persona utiliza una aplicación en un entorno más lúdico, otros factores la motivan, como lo fácil que es usar esa aplicación.

Capítulo 5: Conclusiones y trabajo futuro

La tecnología de realidad aumentada no se ha utilizado intensivamente en la mayoría de las áreas de la ingeniería; por lo tanto, su potencial aún no se ha explotado por completo. Los educadores interesados en esta tecnología, con los resultados entregados en la revisión sistemática **(P.I)**, pueden tomar decisiones informadas al considerar diferentes aspectos de las aplicaciones, desde sus usos educativos hasta cuestiones técnicas. Se necesitan más aplicaciones de realidad aumentada con características más avanzadas para fomentar la adopción de los instructores. Los desarrolladores y los investigadores deben hacer un esfuerzo para construir aplicaciones con características más sofisticadas para explotar por completo el potencial de esta tecnología.

En cuanto al primer modelo de aceptación propuesto **(P.IV)**, este permite explicar el papel del *optimismo tecnológico* y la *innovación tecnológica* en la aceptación de la tecnología de realidad aumentada entre los estudiantes de ingeniería. Los resultados sugieren que las *normas subjetivas* tienen un efecto positivo en el *optimismo* y la *innovación tecnológica*. Las instituciones de educación superior deben generar conciencia sobre los beneficios de las herramientas tecnológicas en el aprendizaje para crear entornos tecnológicamente amigables y promover una actitud tecnológica optimista. La *actitud hacia el uso* puede ser influenciada por el *optimismo* y *la innovación tecnológica*, y el éxito de la implementación de esta tecnología en la educación en ingeniería debe considerar áreas no abordadas previamente, como la actitud de los miembros hacia las nuevas tecnologías y la influencia institucional en estas actitudes.

Finalmente, se propone una versión extendida de TAM para determinar los factores que explican la aceptación de la tecnología de realidad aumentada en la educación en ingeniería **(P.V)**. Los hallazgos sugieren que el entorno académico puede influir en las creencias de los estudiantes sobre el uso de esta tecnología, aumentando su disposición a utilizarla.

Además, se sugiere que los estudios que demuestran que la realidad aumentada mejora el rendimiento académico deben difundirse entre las comunidades educativas. Se recomienda investigar las variables que explican la *intención de uso* por parte de los académicos y abordar el impacto en el rendimiento académico en el futuro. Además, se sugiere considerar características relevantes de esta tecnología, como los niveles de interactividad y la estabilidad de la aplicación, para analizar su influencia en su aceptación.

Una implementación exitosa de la tecnología de realidad aumentada en la educación de ingeniería debe considerar áreas que no se han abordado anteriormente, como la actitud de los miembros hacia las nuevas tecnologías y la influencia institucional sobre estas actitudes. El uso de una tecnología que se puede percibir como beneficiosa puede aumentar el *optimismo tecnológico* de los estudiantes hacia esta tecnología en un contexto educativo. También se debe considerar cómo la participación de estudiantes tecnológicamente innovadores influye en sus compañeros.

Las instituciones educativas están capacitando a nativos digitales y las aplicaciones de realidad aumentada permiten que las instituciones sean más eficientes en el proceso educativo. Se espera que los futuros ingenieros estén familiarizados con esta y otras tecnologías para hacer frente a la industria 4.0.

En el futuro, pueden investigarse los factores que influyen en la adopción de tecnología entre los académicos y considerar las características relevantes de la tecnología (por ejemplo, niveles de interactividad o estabilidad de la aplicación) para analizar su influencia en su aceptación.

Como limitación, esta investigación se llevó a cabo en el contexto de un país en desarrollo. En el futuro, los resultados de este estudio pueden compararse con otros países en contextos más amplios.

En resumen, la adopción de la tecnología de realidad aumentada en la educación en ingeniería aún se encuentra en proceso y se necesitan más investigaciones y desarrollos para aprovechar su potencial.

Publicaciones

Publicación I

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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: $N = 42$.

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: $N = 42$.

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.

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].

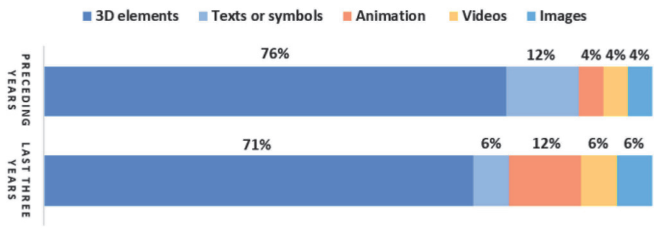

Fig. 1. Media representation—last three years versus preceding years.

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: $N = 42$.

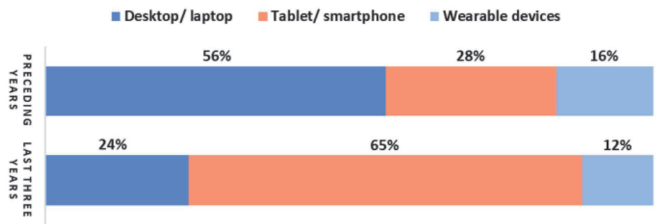

Fig. 2. Computing device—last three years versus preceding years.

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 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: $N = 42$.

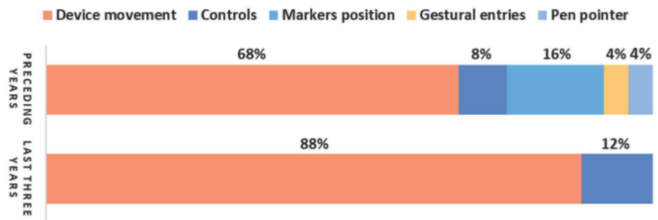

Fig. 3. User input—last three years versus preceding years.

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].

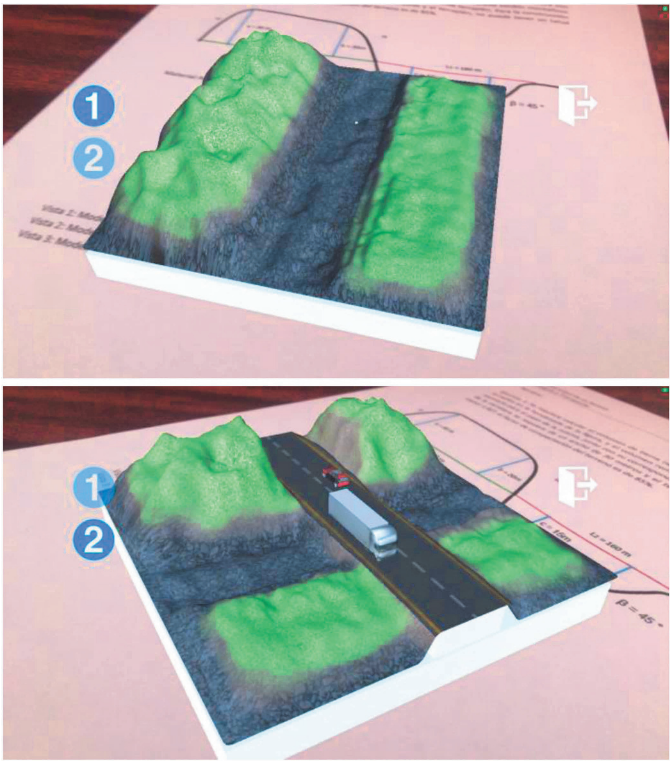

Fig. 4. Augmented visibility's example. Two AR views are shown of a loading and transportation exercise in engineering. The objective is to visualize a small mountain before and after the construction of a road. That can help the student calculate the volume of earth required to build the road with an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

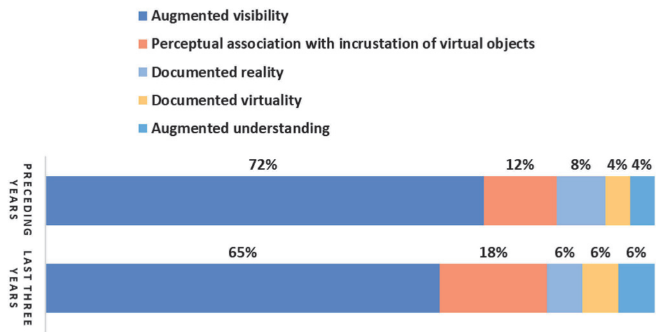

Fig. 5. Functional characteristics—last three years versus preceding years.

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

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: $N = 10$.

without performing further computations (e.g., voltage or current).

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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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,

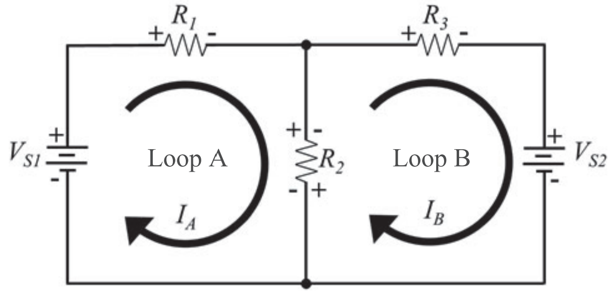

Fig. 1. Resistive circuit with loop method.

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.

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

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

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

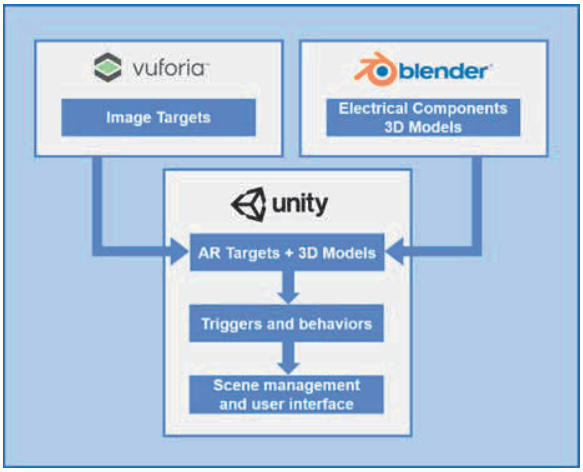

Fig. 2. App's architecture.

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).

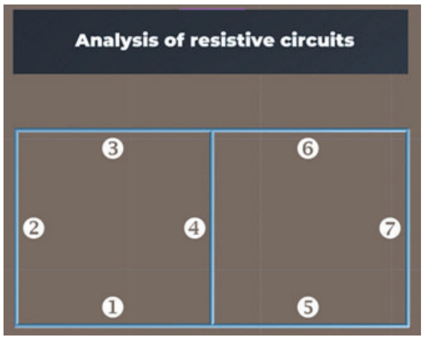

Fig. 3. Unity circuit composed of seven branches.

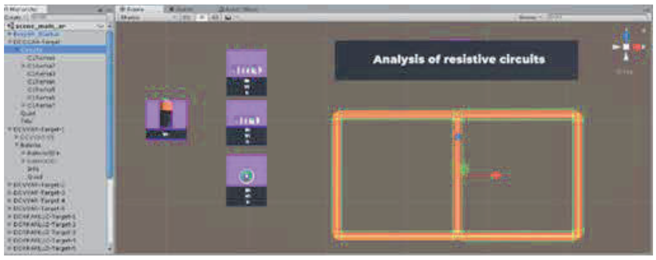

Fig. 4. AR objects with their respective colliders.

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* ().

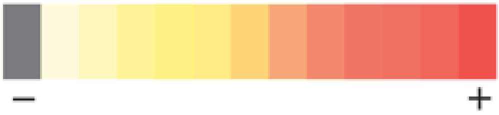

Fig. 5. Values scale of current intensity.

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.

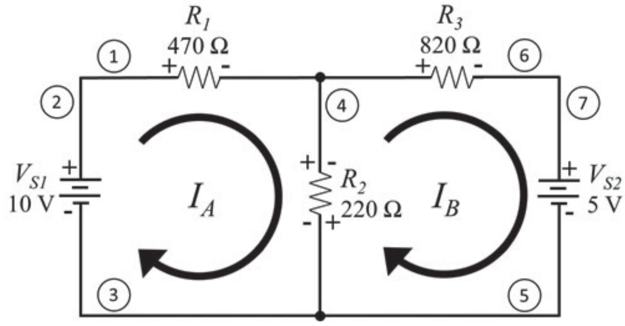

Fig. 6. Suggested exercise. Circles identify the number of each branch.

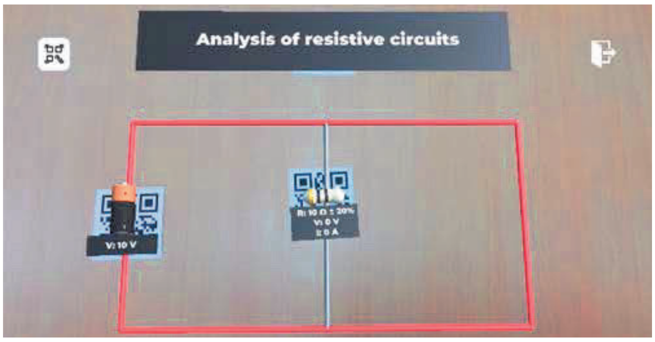

Fig. 7. Circuit with the first objects, with default values.

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

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).

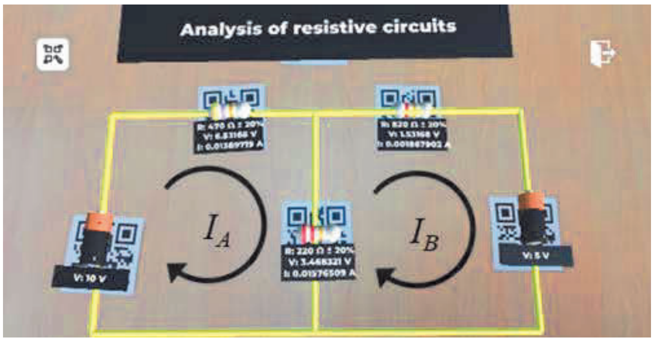

Fig. 9. Circuit of the proposed exercise, with AR objects' values resulting.

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.

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.

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*

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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Publicación 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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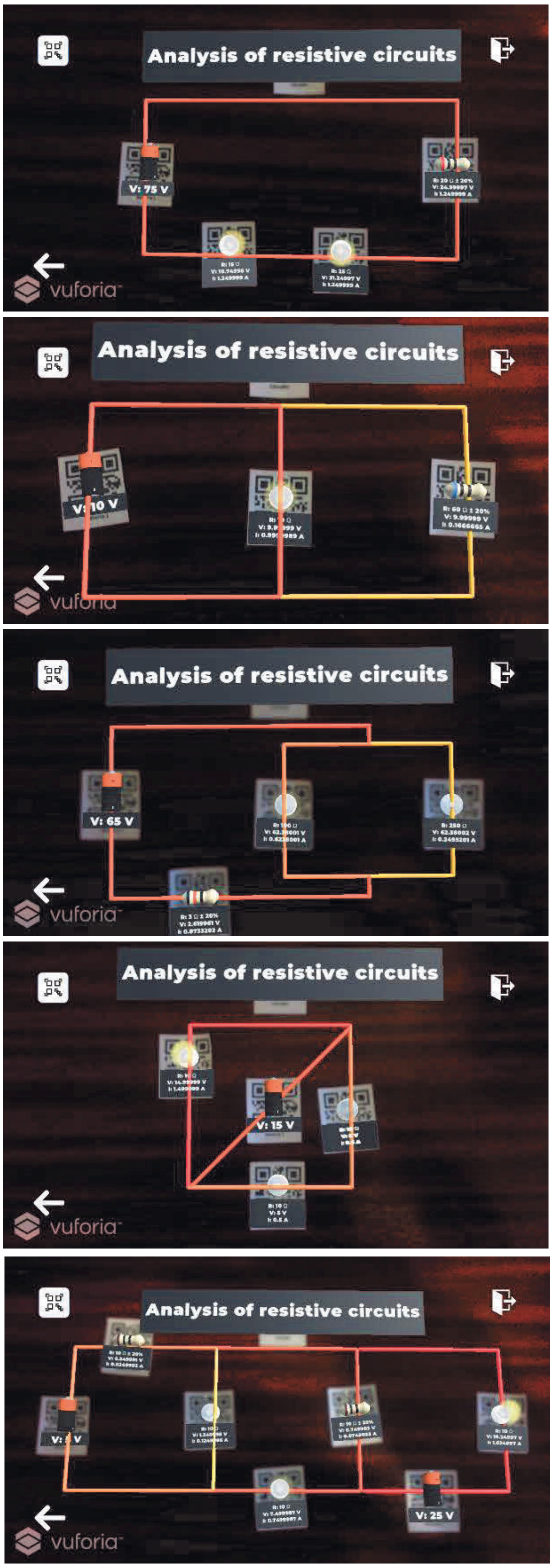

Figure 1: Interactive AR app

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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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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Augmented reality; technology acceptance; engineering; education; interactive app

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.

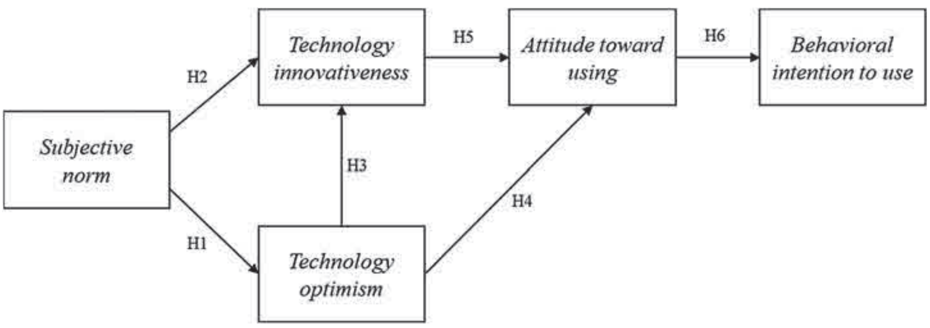

Figure 1. Research Model.

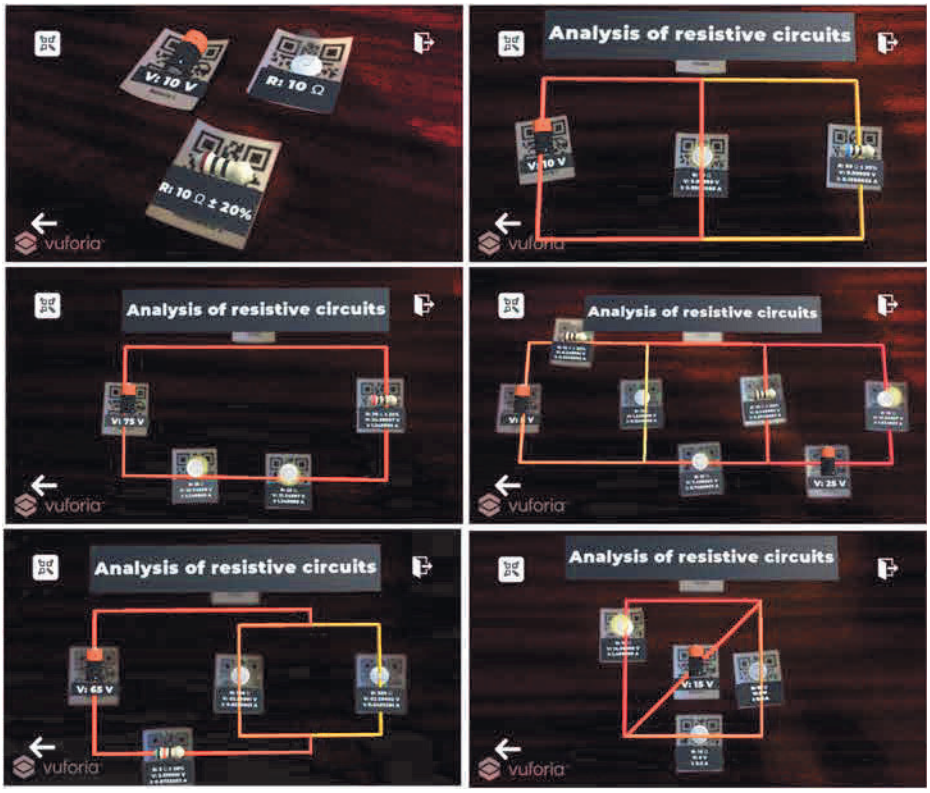

Figure 2. Interactive AR app.

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

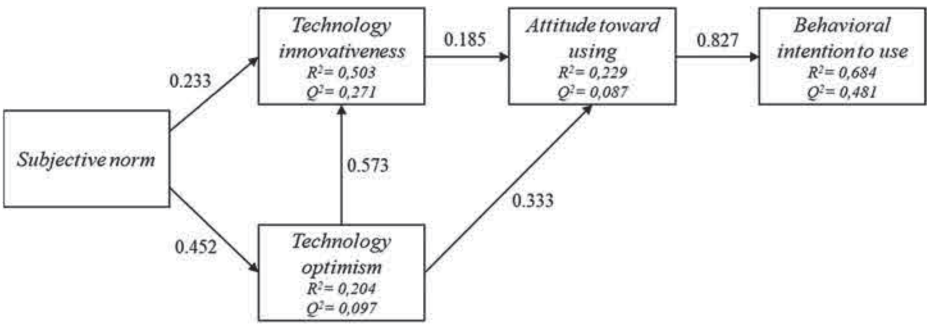

Figure 3. Resulting Research Model.

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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Publicación V

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electronics

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.

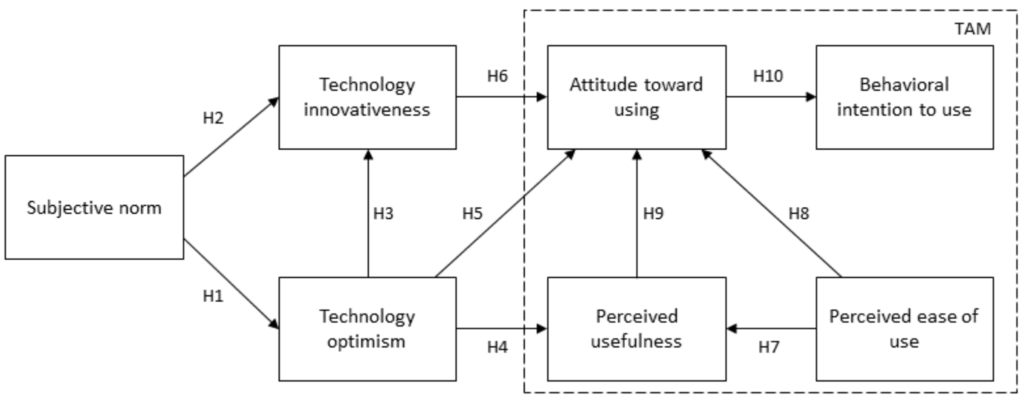

Figure 1. Research model.

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).

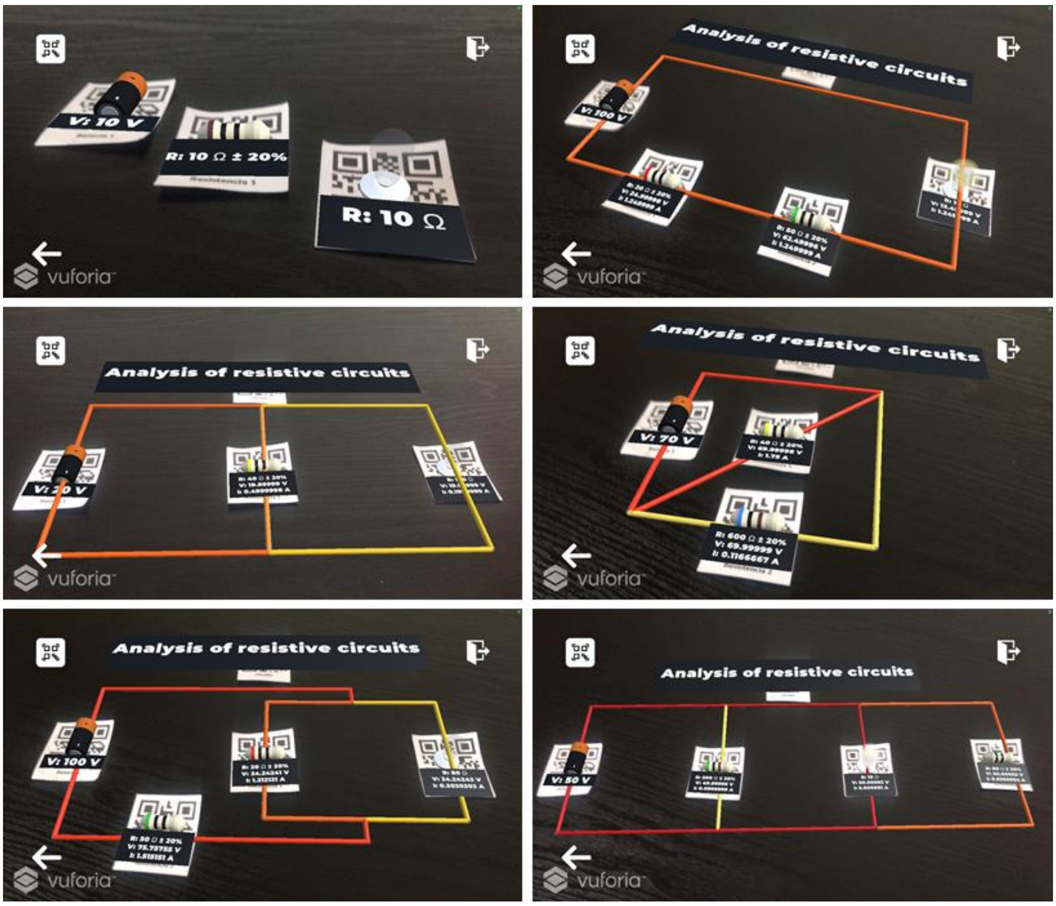

Figure 2. Interactive AR app.

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

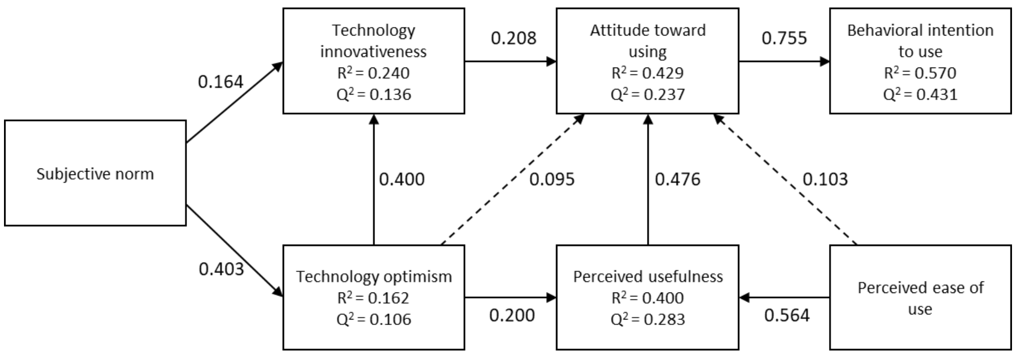

Figure 3. Resulting research model. A dashed arrow shows non-significant paths.

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.

Author Contributions: A.Á.-M.: Conceptualization, Investigation, Methodology, Formal Analysis, Software, Data Curation, Writing—Original Draft. J.Á.V.-I.: Conceptualization, Formal Analysis, Writing—Review and Editing. M.C.-V.: Methodology, Formal Analysis, Writing—Review and Editing. All authors have read and agreed to the published version of the manuscript.

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