UNIVERSIDAD DE SALAMANCA

DEPARTAMENTO DE INFORMÁTICA Y AUTOMÁTICA
FACULTAD DE CIENCIAS

TESIS DOCTORAL

Desarrollo y Evaluación de Entornos Virtuales Aplicados a la Ciencia e Ingeniería de Materiales

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A mis hijos.

Tabla de contenido

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El camino hasta alcanzar el grado de doctor conlleva realizar un esfuerzo constante que debe ser sostenido a lo largo de los años en que transcurre el desarrollo de la tesis doctoral. El sacrificio requerido para llevar a cabo un proyecto de tal magnitud resulta evidente para cualquiera. Sin embargo, una de las recompensas alcanzadas al final del camino tiene un valor inconmensurable, pues consiste nada menos que en comprender el origen del conocimiento formal, académico, y en adquirir la capacidad de contribuir a su creación. No obstante, por más empeño que se tenga, no sería posible concluir con éxito la empresa que lleva a pertenecer a la comunidad de doctores sin el apoyo del entorno personal. Es por ello por lo que resulta una cuestión de justicia agradecer a aquellas personas que, de un modo u otro, han contribuido a que haya llegado hasta este punto.

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1. Tesis Doctoral por Compendio de Artículos Publicados

Esta tesis doctoral se presenta bajo el formato de compendio de artículos publicados en revistas de reconocido prestigio internacional. Los trabajos académicos que conforman el presente compendio se exponen a continuación:

1. Título: Reality-Virtuality Technologies in the Field of Materials Science and Engineering

   Autores: Jamil Extremera (Universidad de Salamanca, España), Diego Vergara (Universidad Católica de Ávila, España), Sara Rodríguez (Universidad de Salamanca, España), Lilian P. Dávila (University of California at Merced, Estados Unidos).

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2. Título: Virtual and Augmented Reality Environments to Learn the Fundamentals of Crystallography

   Autores: Jamil Extremera (Universidad de Salamanca, España), Diego Vergara (Universidad Católica de Ávila, España), Lilian P. Dávila (University of California at Merced, Estados Unidos), Manuel P. Rubio (Universidad de Salamanca, España).

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   Autores: Diego Vergara (Universidad Católica de Ávila, España), Jamil Extremera (Universidad de Salamanca, España), Manuel P. Rubio (Universidad de Salamanca, España), Lilian P. Dávila (University of California at Merced, Estados Unidos).

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4. Título: The Technological Obsolescence of Virtual Reality Learning Environments

   Autores: Diego Vergara (Universidad Católica de Ávila, España), Jamil Extremera (Universidad de Salamanca, España), Manuel P. Rubio (Universidad de Salamanca, España), Lilian P. Dávila (University of California at Merced, Estados Unidos).

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2. Autorización de los Directores y Aceptación de los Coautores

El director y la codirectora de la presente tesis doctoral, titulada *Desarrollo y Evaluación de Entornos Virtuales Aplicados a la Ciencia e Ingeniería de Materiales* y cuyo autor es Jamil Extremera Nedjar, autorizamos a que la misma sea presentada bajo la modalidad de compendio de artículos al disponer de los siguientes trabajos publicados:

1. Extremera, J.; Vergara, D.; Rodríguez, S.; Dávila, L.P. Reality-Virtuality Technologies in the Field of Materials Science and Engineering. Appl. Sci. 2022, 12, 4968.
2. Extremera, J.; Vergara, D.; Dávila, L.P.; Rubio, M.P. Virtual and Augmented Reality Environments to Learn the Fundamentals of Crystallography. Crystals 2020, 10, 456.
3. Vergara, D.; Extremera, J.; Rubio, M.P.; Dávila, L.P. Meaningful Learning Through Virtual Reality Learning Environments: A Case Study in Materials Engineering. Appl. Sci. 2019, 9, 4625.
4. Vergara, D.; Extremera, J.; Rubio, M.P.; Dávila, L.P. The Technological Obsolescence of Virtual Reality Learning Environments. Appl. Sci. 2020, 10, 915.

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3. Listado de Abreviaturas

A lo largo de este trabajo se han empleado las siguientes siglas:

AR	Augmented Reality
BCC	Body-Centered Cubic
CAVE	Cave Automatic Virtual Environment
CCDC	Cambridge Crystallographic Data Center
CL	Crystal Lattices
COD	Crystallography Open Database
DC	Diamond Cubic
FCC	Face-Centered Cubic
HCP	Hexagonal Close-Packed
HMD	Head Mounted Display
ICT	Information and Communication Technology
IVR	Immersive Virtual Reality
KPI	Key Performance Indicator
MEMS	Micro-Electro-Mechanical Systems
MR	Mixed Reality
MSE	Materials Science and Engineering
NIVR	Non-Immersive Virtual Reality
OOP	Object-Oriented Programming

PC	Personal Computer
RVT	Reality-Virtuality Technology
SLR	Systematic Literature Review
SMA	Shape Memory Alloy
TEM	Transmission Electron Microscope
TPD	Ternary Phases Diagrams
UE4	Unreal Engine 4
VL	Virtual Laboratory
VR	Virtual Reality
VRLE	Virtual Reality Learning Environment
WOS	Web of Science

4. Resumen

El desarrollo y mejoras exponenciales que han experimentado las tecnologías de la información y la comunicación (ICT, del término inglés *Information and Communication Technologies*) en las últimas décadas ha traído aparejada la aparición de dispositivos que ofrecen funcionalidades difícilmente imaginables a finales del siglo pasado. Estas innovaciones tecnológicas han penetrado, en mayor o en menor media, en prácticamente todas las capas de la sociedad transformando la mayoría de los ámbitos profesionales, científicos, educativos, culturales, etc. Al amparo de esta transformación tecnológica, las tecnologías de realidad-virtualidad (RVT, del término inglés *Reality-Virtuality Technologies*) con mayor presencia en el mercado (es decir, realidad virtual (VR, del término inglés *Virtual Reality*), realidad aumentada (AR, del término inglés *Augmented Reality*) y realidad mixta (MR, del término inglés *Mixed Reality*)) han experimentado una notable mejora y abaratamiento, factores que han propiciado su expansión en numerosos ámbitos. La Ciencia e Ingeniería de Materiales (MSE, del término inglés *Materials Science and Engineering*) no es ajena a esta expansión de las RVT, siendo actualmente posible encontrar numerosos ejemplos de uso de estas tecnologías circunscritas a la MSE. Esta tesis doctoral aborda la investigación de diferentes aspectos del desarrollo y uso de herramientas basadas en RVT empleadas dentro del ámbito de la MSE.

La primera parte de esta investigación persigue conocer el estado del arte en el uso de las RVT en el ámbito de la MSE para, de este modo, facilitar la apertura de nuevas líneas de investigación y la adquisición de ideas de desarrollo. Para ello, en primer lugar, se han analizado las aplicaciones basadas en RVT circunscritas a la MSE desarrolladas entre 2010 y 2021, con independencia de su propósito. Este análisis ha permitido conocer en qué áreas de la MSE se enmarcan las aplicaciones basadas en RVT, a qué sectores se dirigen, qué RVT emplean y qué propiedades de las mismas explotan. En segundo lugar, se analizaron las aplicaciones basadas en VR o AR que se han desarrollado hasta el año 2020 destinadas a dar soporte a la enseñanza de cristalografía. Además, se ha desarrollado una aplicación basada en VR orientada a facilitar la enseñanza de las redes de Bravais y se ha propuesto un procedimiento de uso y evaluación en el aula.

La segunda parte de esta investigación analiza el proceso de creación de laboratorios virtuales destinados a facilitar la enseñanza de MSE en los grados de ingeniería. En particular, esta parte de la investigación analiza qué factores deben ser tenidos en cuenta por los docentes cuando crean laboratorios virtuales para que logren maximizar el aprendizaje significativo de los estudiantes, es decir, que sean capaces de comprender mejor y por más tiempo aquello que se les enseña. Para alcanzar este objetivo, por una parte, se analizó el proceso de desarrollo de diferentes laboratorios virtuales destinados a dar soporte a la enseñanza de ensayos de materiales. Por otra parte, se analizaron los resultados de los cuestionarios respondidos por diferentes grupos de alumnos un año después de usar los laboratorios virtuales analizados. De este modo ha sido posible establecer una serie de aspectos que deben ser tenidos en cuenta durante el proceso de desarrollo de las aplicaciones basadas en VR destinadas a facilitar el proceso de enseñanza-aprendizaje de MSE, de manera que se maximice el aprendizaje significativo del alumno.

La tercera parte de esta investigación ahonda en el modo en que afecta el paso del tiempo a la eficacia formativa de los laboratorios virtuales destinados a dar soporte a la enseñanza de MSE. En este sentido, se han analizado las opiniones vertidas por diferentes grupos de estudiantes que utilizaron laboratorios virtuales y se comprobó cómo su motivación por utilizar dichos laboratorios disminuía (y, por tanto, la eficacia formativa de estas herramientas educativas también disminuía) con el transcurso de los años. En esta parte de la investigación se analizó este fenómeno circunscrito a aplicaciones basadas en VR orientadas a facilitar la enseñanza de MSE, constatándose su relación directa con las leyes de evolución del software establecidas por Lehman. El estudio llevado a cabo reveló que, si estas aplicaciones educativas son actualizadas periódicamente empleando herramientas de desarrollo actuales, es posible mantener su atractivo para los estudiantes y con él su eficacia formativa.

5. Abstract

The exponential development and improvements that information and communication technologies (ICT) have undergone in recent decades have brought with them the appearance of devices that offer functionalities that would have been difficult to imagine at the end of the last century. These technological innovations have permeated, to a greater or lesser extent, practically all layers of society, transforming most professional, scientific, educational, cultural, etc. fields. As a result of this technological transformation, the reality-virtuality technologies (RVT) with the greatest presence in the market (i.e., virtual reality (VR), augmented reality (AR) and mixed reality (MR)) have experienced a significant improvement and reduction in price, factors that have led to their expansion in many fields. Materials Science and Engineering (MSE) is no exception to this expansion of VRT, and it is currently possible to find numerous examples of the use of these technologies in MSE. This doctoral thesis investigates different aspects of the development and use of RVT-based tools used in the field of MSE.

The first part of this research aims to know the state of the art in the use of VRT in the field of MSE in order to facilitate the opening of new lines of research and the acquisition of development ideas. To this end, first of all, it has been analysed the applications based on RVT in the field of MSE developed between 2010 and 2021, regardless of their purpose. This analysis has provided insight into which areas of the MSE the RVT-based applications fall into, which sectors they target, which RVT they use and which properties they exploit. Secondly, the VR or AR-based applications that have been developed up to 2020 to support the teaching of crystallography were analysed. In addition, a VR-based application has been developed to facilitate the teaching of Bravais lattices and a procedure for its use and evaluation in the classroom has been proposed.

The second part of this research analyses the process of creating virtual laboratories aimed at facilitating the teaching of MSE in engineering degrees. In particular, this part of the research analyses which factors should be taken into account by teachers when creating virtual laboratories in order to maximise students' meaningful learning, i.e., that

they are able to understand better and for longer what they are taught. To achieve this objective, on the one hand, the development process of different virtual laboratories designed to support the teaching of materials testing was analysed. On the other hand, the results of the questionnaires answered by different groups of students one year after using the virtual laboratories analysed were examined. In this way, it has been possible to establish a series of aspects that should be taken into account during the development process of VR-based applications aimed at facilitating the MSE teaching-learning process, so as to maximise meaningful learning of students.

The third part of this research explores how the passage of time affects the learning effectiveness of virtual laboratories designed to support MSE teaching. In this regard, the opinions expressed by different groups of students who used virtual laboratories were analysed and it was found that their motivation to use these laboratories decreased (and, therefore, the learning effectiveness of these educational tools also decreased) over the years. This part of the research analysed this phenomenon limited to VR-based applications aimed at facilitating the teaching of MSE and found a direct relationship with the laws of software evolution established by Lehman. The study revealed that, if these educational applications are regularly updated using current development tools, it is possible to maintain their desirability for students and thus their educational effectiveness.

6. Introducción

Cuando se busca literatura científica centrada en el uso de las tecnologías de realidad-virtualidad (RVT, del término inglés *Reality-Virtuality Technologies*) en el ámbito de la Ciencia e Ingeniería de Materiales (MSE, del término inglés *Materials Science and Engineering*), es posible formarse la idea de que la mayor parte de los trabajos están enfocados a dar soporte a la enseñanza universitaria. Si esta idea se confirmara, se pondría de relieve que el uso de las RVT tiene una importancia notable en la enseñanza de MSE. De este modo sería posible llegar a la conclusión de que resulta de interés conocer y mejorar los procesos de desarrollo de las herramientas basadas en RVT destinadas a mejorar el aprendizaje de MSE. El estudio de estos procesos de desarrollo debería permitir crear herramientas más efectivas a nivel formativo que las actuales, lo cual incluye, por una parte, mejorar el nivel de conocimiento adquirido por los alumnos mediante su uso y, por la otra parte, prevenir que los estudiantes dejen de sentirse motivados a utilizarlas por apreciarlas como obsoletas cuando estas tienen algunos años de antigüedad.

En base a las suposiciones anteriores, en esta tesis doctoral se ha investigado una serie de conceptos relacionados con el desarrollo y la evaluación de entornos virtuales aplicados a la MSE. En particular, se ha estudiado minuciosamente cuál es el estado del arte y se ha confirmado, entre otros aspectos, que la mayor parte de las aplicaciones basadas en RVT en el ámbito de la MSE están orientadas a dar soporte a la enseñanza de diferentes áreas de esta. Confirmada de esta manera la importancia que tienen las RVT como medio para mejorar el proceso de enseñanza-aprendizaje de la MSE, se han estudiado los aspectos relacionados con el desarrollo de herramientas educativas que permiten mejorar su eficacia formativa y prevenir que sean percibidas como anticuadas por los estudiantes a medida que pase el tiempo (y, en consecuencia, se sientan desmotivados a utilizarlas).

Esta tesis doctoral se ha estructurado del siguiente modo:

- Los subapartados 6.1 a 6.5 ofrecen una introducción al contexto en el que se desarrolla esta investigación.
- El apartado 7 expone los problemas abordados.
- El apartado 8 enuncia las hipótesis planteadas, así como los objetivos que se pretenden alcanzar para obtener sus confirmaciones (y, con ellas, las soluciones a los problemas planteados en el apartado 7).
- Los apartados 9, 10, 11 y 12 corresponden a las publicaciones acreditativas de la investigación realizada, y presentan sendos resúmenes de los 4 artículos empleados en el compendio de artículos. A continuación de cada resumen se incluye el artículo completo.
- El apartado 13 expone las conclusiones alcanzadas a lo largo de la investigación, así como el trabajo futuro que se pretende desarrollar.
- El apartado 14 muestra los indicadores de calidad de las revistas en que se han publicado los 4 artículos empleados para el compendio, así como el número de citas y visitas que han tenido cada uno de ellos.
- El apartado 15 expone la bibliografía empleada en la redacción de esta memoria.
- El apartado 16 lista otros trabajos publicados en congresos y revistas científicas a lo largo del desarrollo de la tesis doctoral.

6.1. Tecnologías de Realidad-Virtualidad Actuales

El concepto de "continuo virtual", que clasifica las diferentes RVT en función de los niveles de realidad y de virtualidad que gestiona cada una de ellas (Figura 1), fue acuñado por Paul Milgram y Fumio Kishino en 1994 [1]. Así, en un extremo del continuo virtual se encuentra el mundo real, mientras que en el opuesto se encuentran los entornos completamente virtuales correspondientes al concepto de realidad virtual (VR, del término inglés *Virtual Reality*). Entre ambos extremos se encuentran otros conceptos, como por ejemplo realidad aumentada (AR, del término inglés *Augmented Reality*) y virtualidad aumentada, entendiéndose como realidad mixta (MR, del término inglés *Mixed Reality*) la unión de ambos. Es posible afirmar que las RVT empleadas actualmente son VR, AR y MR [2].

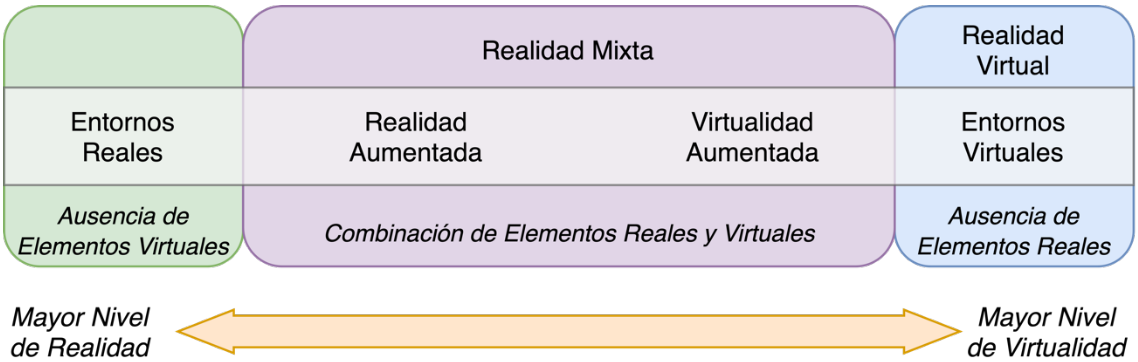

Figura 1. Representación gráfica del concepto de continuo virtual.

La VR es una tecnología que permite al usuario interactuar con entornos tridimensionales totalmente virtuales generados por ordenador [3], pudiendo así vivir experiencias en un mundo más allá del real [4]. Dentro de la RV, es habitual diferenciar entre VR no inmersiva (NIVR, del término inglés *Non-Immersive Virtual Reality*) y VR inmersiva (IVR, del término inglés *Immersive Virtual Reality*) [5,6]. En el caso de la NIVR, los entornos virtuales se muestran a través de una pantalla, como ocurre en la mayoría de los videojuegos 3D actuales para ordenador, por ejemplo. Por su parte, la IVR facilita en el usuario la ilusión de sentirse completamente inmerso en el entorno virtual, dándole la sensación de estar presente [7]. Esta tecnología se implementa principalmente mediante gafas de realidad virtual (conocidas como *head-mounted displays*, HMDs) que se colocan frente a los ojos del usuario, o mediante sistemas tipo CAVE, en los cuales se proyectan imágenes en varias paredes de una sala que el usuario visualiza en tres dimensiones con la ayuda de gafas estereoscópicas [5,8].

La tecnología de AR posibilita visualizar en tiempo real el mundo físico “aumentado” mediante la inclusión de elementos virtuales creados con ordenador [9], tales como objetos 3D, textos, indicadores, etc. Actualmente la AR se implementa principalmente a través de teléfonos inteligentes, tabletas y, en menor medida, HMDs [10,11].

La tecnología de MR es conceptualmente cercana a la AR ya que también emplea la inclusión de elementos virtuales en el mundo físico en tiempo real. No obstante, la MR persigue que los elementos virtuales no estén simplemente superpuestos al entorno real (como ocurre con la AR), sino que los objetos virtuales sean indistinguibles de los reales [12]. Cuando se implementa la MR, los objetos virtuales deben estar integrados en el mundo físico [11] y, en consecuencia, la coherencia visual desempeña un papel crucial en esta tecnología [13]. La MR permite al usuario interactuar en tiempo real tanto con objetos físicos como con objetos virtuales, de modo que los objetos reales puedan manipular a los virtuales [12]. Para comprender la diferencia entre AR y MR, piénsese en un objeto virtual situado bajo una mesa real; empleando AR, dicho objeto se vería superpuesto a la mesa, siendo además visible para el usuario en todo momento y desde cualquier ángulo; empleando MR, la mesa tapará al objeto si este se mirase desde arriba, por lo que solamente sería visible para el usuario si se mirase debajo de la mesa [12]. El principal sistema comercial que permite implementar MR actualmente es Microsoft HoloLens [12,13], cuyo visor es un HMD de óptica transparente que mezcla los elementos reales y virtuales a través de un combinador óptico instalado en la visual del usuario [13].

6.2. Uso de las Tecnologías de Realidad-Virtualidad en la Ciencia e Ingeniería de Materiales

El uso de las RVT en el ámbito de la ingeniería ha experimentado un crecimiento notable en las últimas décadas [14]. En efecto, si se realiza una búsqueda de literatura científica en Scopus que contenga los términos “virtual reality”, “augmented reality” o “mixed reality” en su título, resumen o palabras clave, y se restringen los resultados a los que se encuentran en el ámbito de ingeniería, se observa que a partir de 2010 se produce un crecimiento en el número de trabajos publicados, acentuándose dicho crecimiento a partir de 2015 (Figura 2). Nótese que la década de 2010 coincide con la expansión de los teléfonos inteligente y las tabletas, con el surgimiento de sistemas de VR asequibles destinados al gran público y con la aparición de motores de videojuegos relativamente sencillos de utilizar para crear objetos y entornos virtuales interactivos.

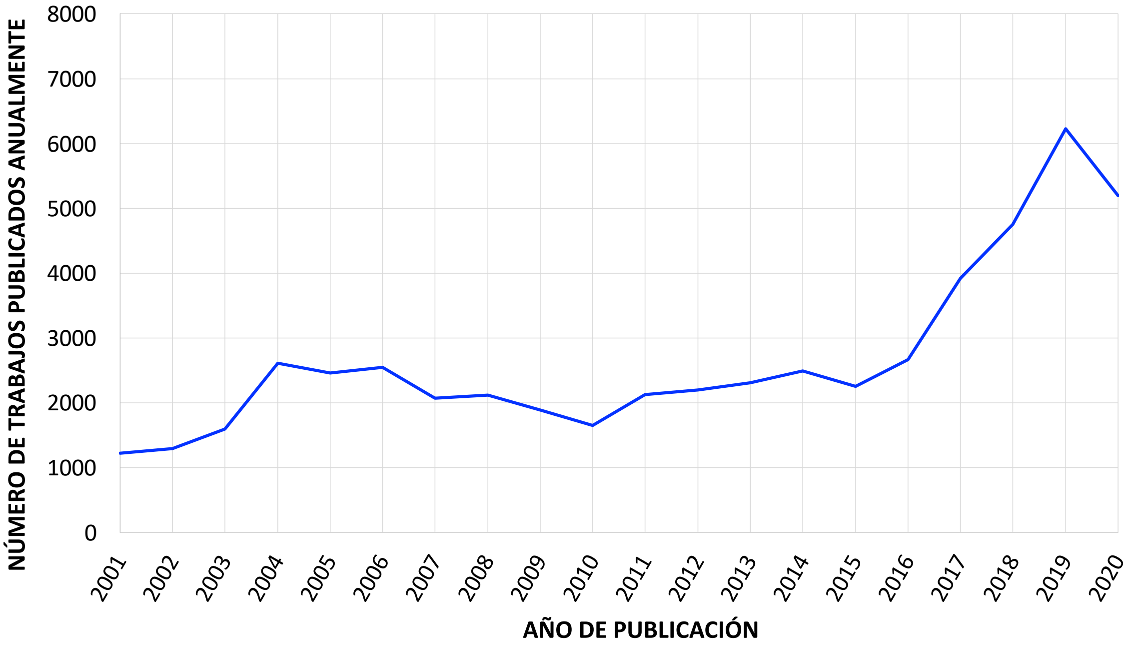

Figura 2. Número de trabajos académicos publicados anualmente con los términos “virtual reality”, “augmented reality” o “mixed reality” en su título, resumen o palabras clave, indexados en Scopus desde 2001 hasta 2020, restringidos al ámbito de la ingeniería.

Particularizando en la MSE, es posible encontrar numerosos ejemplos de trabajos académicos en los cuales se describen laboratorios virtuales [15] centrados en la simulación de ensayos de tracción [16,17], ensayos de compresión [18], ensayos de impacto [19,20], ensayos de dureza [19,20], análisis microscópico [19,20] o ensayos no destructivos [21,22], entre otros. También es posible encontrar laboratorios virtuales destinados a facilitar la comprensión o visualización espacial de conceptos que en ocasiones implican entender disposiciones espaciales complejas. Ejemplos de este tipo de laboratorios son los centrados en las estructuras cristalográficas [23,24], diagramas de fases [25,26], nanomateriales [27,28], o procesos de fabricación de materiales [29]. Cuando se analizan estos laboratorios virtuales, es posible comprobar que todos ellos hacen uso de una o varias de las siguientes propiedades inherentes a las RVT: (i) facilitan la visión espacial, es decir, permiten al usuario visualizar formas o disposiciones espaciales complejas que pueden ser difíciles de comprender; (ii) permiten al usuario interactuar con elementos virtuales, bien correspondan estos a representaciones de objetos físicos tangibles o bien correspondan a representaciones de conceptos abstractos; y (iii) posibilitan la creación de simuladores de dispositivos e instalaciones reales, tales como herramientas, máquinas o laboratorios enteros.

6.3. Entornos de Aprendizaje Basados en Realidad Virtual

Un laboratorio virtual basado en VR destinado a dar soporte a la enseñanza de MSE es un tipo particular de entorno de aprendizaje basado en VR (VRLE, del término inglés *Virtual Reality Learning Environment*). Los VRLEs empleados en la enseñanza de MSE presentan una serie de ventajas entre las que destacan las siguientes [17,30,31]: (i) permiten solventar las deficiencias ligadas a la masificación de las clases prácticas de laboratorio; (ii) proporcionan un medio para complementar el aprendizaje que los estudiantes adquieren las clases de prácticas, ayudando así a superar las limitaciones de tiempo que en muchas ocasiones existen a la hora de utilizar las máquinas de ensayo de materiales en los laboratorios tradicionales; (iii) ofrecen visualización de alta calidad de elementos que pueden ser difíciles de mostrar en el aula tradicional; (iv) permiten a los profesores desarrollar aplicaciones didácticas ad hoc en los VRLEs para reforzar determinados conocimientos; (v) aumentan el compromiso y la motivación de los estudiantes acercándolos a un entorno amigable y familiar (ya que es similar a un videojuego); (vi) mejoran la calidad de la enseñanza; (vii) ayudan a reducir el coste asociado a las clases de laboratorio modernas, pues evitan la necesidad de adquirir equipos que pueden ser muy costosos; y (viii) disminuyen el riesgo de que los estudiantes o los profesores sufran daño físico durante el manejo de las máquinas de ensayo. Además, diferentes estudios apuntan a que los VRLEs pueden constituir herramientas educativas con una alta eficacia a nivel formativo, ayudando así a mejorar el proceso de enseñanza-aprendizaje en la universidad [15,17,18,27,28,32–38].

Trabajos previos demuestran que el diseño de un VRLE desempeña un papel crucial en el desarrollo del proceso de enseñanza-aprendizaje [23,39,40] (por ejemplo, es posible afirmar que existe una relación directa entre el diseño de un VRLE y la motivación generada en el usuario para seguir utilizándolo [23]). Es por ello por lo que diferentes trabajos académicos han abordado la cuestión concerniente al proceso de creación de e implementación en el aula de los VRLEs [14,15,27,28,37,38,41–46].

6.4. Realidad Virtual y Aumentada en la Enseñanza de Cristalografía

El proceso de enseñanza-aprendizaje de estructuras cristalográficas se caracteriza por la dificultad de recrear mentalmente distribuciones espaciales complejas [47]. Tanto la distribución espacial de los átomos que componen las celdas unidad como las estructuras que se forman al unirlas pueden ser conceptos difíciles de entender para muchos alumnos cuando se utilizan métodos de enseñanza basados únicamente en representaciones gráficas bidimensionales (como sería el caso de las ilustraciones de los libros de texto). Con el fin de paliar este problema, tradicionalmente se han empleado modelos de plástico o madera que representan estructuras cristalográficas, aunque este método presenta desventajas tales como el relativamente alto coste de crear nuevos modelos [48] o las limitaciones de su manipulación (por ejemplo, en los modelos de plástico o madera no es posible crear secciones en tiempo real para visualizar la densidad planar o lineal).

Las herramientas didácticas basadas en VR y AR han probado ser especialmente útiles cuando se emplean para mejorar la comprensión espacial de los estudiantes, ayudándoles a comprender conceptos relacionados con estructuras espaciales complejas [26,47,49–52]. En consecuencia, las últimas décadas han sido testigo del desarrollo de herramientas basadas en VR y AR orientadas a mejorar la comprensión de las estructuras cristalográficas, tanto entre estudiantes como entre investigadores. Así, es posible encontrar ejemplos de repositorios de estructuras cristalográficas como el Crystallography Open Database [53] o el que está alojado en el Cambridge Crystallographic Data Center [54]. Los datos descargados de estos repositorios pueden ser procesados mediante programas como VESTA [55] o Mercury [56,57], los cuales ofrecen multitud de opciones de análisis cristalográfico, incluyendo diferentes posibilidades de visualización de los modelos virtuales 3D de las estructuras cristalográficas.

6.5. Las Leyes de Lehman de la Evolución del Software

La obsolescencia tecnológica es un fenómeno que afecta a cualquier dispositivo que emplee algún tipo de software ya que el mismo es actualizado constantemente. Es sencillo observar, por ejemplo, que la mayoría de los programas informáticos reciben varias actualizaciones durante su vida útil, o que el aspecto y funcionalidades de las páginas web cambia con el paso de los años. Un ejemplo claro de cómo evoluciona el software se encuentra en los sistemas operativos de Microsoft: MS-DOS, cuyo funcionamiento se basaba en la introducción de comandos escritos por parte del usuario, fue reemplazado por Windows, en el cual el usuario interactúa a través de elementos gráficos. Otro ejemplo se encuentra en las páginas web: si se comparan las páginas de finales de la última década del siglo XX con las actuales, se observa que las últimas cuentan con un aspecto adaptado a los gustos contemporáneos, enlaces a redes sociales (inexistentes hasta el siglo XXI), multitud de imágenes y vídeos de alta calidad (imposibles de incluir en las páginas web antes de la difusión del internet de alta velocidad), o modernos protocolos de seguridad, entre otros. Esta evolución del software se puede observar, además de en sitios web, en sistemas operativos, aplicaciones móviles o de escritorio, videojuegos, interfaces de usuario, firmwares, etc.

Tal como señalaron Lehman y Ramil [58], la transformación en el uso que se hace del hardware implica que su dominio de uso y sus aplicaciones también cambien. Por ejemplo, un teléfono móvil de los años 90 se empleaba principalmente para realizar llamadas telefónicas, mientras que los teléfonos móviles actuales son empleados para multitud de tareas en diferentes ámbitos. La evolución del software es un fenómeno que puede ser estudiado de sistemáticamente dado que en cierta medida es posible encontrar patrones de regularidad [58]. De hecho, existen numerosos estudios centrados en este campo que investigan, entre otros: el modo en que el software evoluciona [59,60], el desarrollo de métodos para llevar a cabo la evolución de determinado software [61], o técnicas para monitorear dicha evolución [62,63].

Entre los estudios que conciernen a la evolución del software destaca el trabajo iniciado por Lehman a finales de los años 60 y que continuó por varias décadas [64–66], del cual surgieron 8 leyes conocidas como leyes de Lehman de evolución del software. Las leyes de Lehman se han utilizadas en numerosos trabajos centrados en la evolución del software, bien sea para estudiarlas [67–71], bien sea usándolas como base para nuevas investigaciones [72–76]. La primera y séptima leyes de Lehman resultan relevantes para la investigación presentada en esta tesis doctoral (ya que tienen una influencia directa en las aplicaciones basadas en RVT destinadas a dar soporte a la enseñanza de MSE), y establecen lo siguiente [66]:

- Primera ley de Lehman: un programa informático debe ser adaptado continuamente o de lo contrario su uso se volverá cada vez más insatisfactorio para los usuarios. Esto implica que cuando se pretende que un software sea útil a lo largo de los años este debe ser adaptado a los requisitos del entorno en que va a utilizarse. Un ejemplo de ello se encuentra en los botones de compartir (a través de redes sociales, mensajería instantánea, etc.) que incluyen muchas de las aplicaciones y páginas web actuales, función que era inexistente dos décadas atrás.
- Séptima ley de Lehman: los usuarios percibirán que el nivel de calidad de un programa informático decrece con el paso del tiempo a menos que se lleve a cabo un mantenimiento riguroso del programa y sea adaptado a un entorno de operación cambiante. Es decir, un software que ha sido percibido positivamente por los usuarios durante un periodo de tiempo puede llegar a ser percibido negativamente por estos mismos usuarios con el paso del tiempo. Esto es debido a que los criterios de aceptación de un programa informático por parte de los usuarios frecuentemente varían con el paso del tiempo.

Como puede verse, existe una relación directa entre estas dos leyes y las herramientas didácticas basadas en RVT, pues uno de los factores claves que determinan su eficacia formativa radica en el hecho de que los estudiantes tengan una percepción positiva de las mismas (percepción que, si no se toma acción alguna, empeora a medida que pasa el tiempo y se tornan anticuadas).

7. Problemas Abordados

En esta tesis doctoral se abordan tres problemas que investigadores y profesores del ámbito de la MSE enfrentan cuando emplean RVT en sus trabajos de investigación o docencia, que se resumen del siguiente modo:

- Conocer el estado del arte requiere una gran inversión de tiempo ya que no existen trabajos que ofrezcan una imagen panorámica de cómo se han implementado hasta el momento las RVT en MSE.

- En numerosas ocasiones los alumnos que han empleado VRLEs como apoyo al aprendizaje de MSE no alcanzan un nivel de aprendizaje significativo suficiente, a causa de lo cual olvidan rápidamente lo aprendido mediante dichos VRLEs.

- La valoración que dan los estudiantes a los VRLEs destinados a dar soporte a la enseñanza de MSE suele ser alta al inicio de su vida útil, pero disminuye a medida que transcurren los años.

Los siguientes apartados describen de manera pormenorizada cada uno de estos problemas.

7.1. Problema 1: Estado del Arte

El número de aplicaciones basadas en RVT que están circunscritas a la MSE ha crecido año tras año, siendo posible hoy en día encontrar numerosos ejemplos realizando búsquedas de trabajos académicos. En este sentido, el investigador que pretende conocer el estado del arte de este tipo de aplicaciones tiene a su alcance una gran cantidad de información que ha sido obtenida por otros grupos de investigación durante un largo periodo de tiempo. Esta información constituye un medio imprescindible para abrir nuevas líneas de investigación, además de una fuente de conocimiento útil para desarrollar nuevas aplicaciones y llevar a cabo el mantenimiento de las existentes.

Un problema que encuentra el investigador que centra su trabajo en el desarrollo de herramientas basadas en RVT aplicadas a la MSE es que, dado que las búsquedas de trabajos académicos arrojan un gran número de resultados, se requiere que invierta una ingente cantidad de tiempo en analizar cada uno de los resultados si quiere tener la certeza de conocer el estado del arte actual antes de iniciar una nueva investigación. El mismo problema encuentran tanto el profesor como el investigador cuando busca información que inspire el desarrollo y mantenimiento de las aplicaciones desarrolladas por ellos mismos.

7.2. Problema 2: Aprendizaje Significativo

Cuando se analiza un número de trabajos académicos lo suficientemente grande en que se relacione el uso de RVT con MSE, se observa que en una gran parte de ellos se describen herramientas educativas, en particular VRLEs. El proceso de desarrollo e implementación en el aula de este tipo de aplicaciones ha sido estudiado en diferentes trabajos que se han centrado en la eficacia formativa de las mismas. En efecto, cuando se emplean VRLEs resulta de gran importancia que los alumnos alcancen un aprendizaje significativo suficiente (es decir, que los conocimientos aprendidos sean comprendidos en su totalidad por los estudiantes y que posteriormente puedan utilizarlos para establecer conexiones con otros conocimientos previamente adquiridos). Sin embargo, existen reportes de profesores indicando que numerosos alumnos que habían empleado VRLEs en el pasado habían olvidado en poco tiempo gran parte de lo aprendido con la ayuda de dichos VRLEs. Así pues, un problema que encuentra el profesor que pretende desarrollar sus propios VRLEs para apoyar la enseñanza de MSE radica en el hecho de que, si bien a corto plazo estas herramientas educativas son efectivas, el nivel de aprendizaje significativo alcanzado con ellas resulta insuficiente en muchos casos y, debido a ello, parte del alumnado olvida lo aprendido en un corto intervalo de tiempo.

7.3. Problema 3: Motivación de los Estudiantes

Es habitual que un profesor que ha desarrollado un VRLE para mejorar la enseñanza de MSE lo emplee año tras año con los diferentes grupos de estudiantes a los que imparte clases. En efecto, este hecho es comprensible si se tiene en cuenta que el diseño y desarrollo de un VRLE es un proceso que puede requiere invertir una cantidad notable de tiempo y recursos, tanto humanos (dedicados principalmente a diseñar, modelar en 3D y a programar), como materiales (esencialmente software de desarrollo y hardware), como económicos (destinados fundamentalmente a adquirir o renovar el hardware o a pagar licencias). No resulta infrecuente encontrar profesores que, tras utilizar VRLEs desarrollados en el seno de su universidad para dar soporte a sus clases, realizan encuestas entre sus estudiantes para conocer su opinión acerca de estas herramientas didácticas. A raíz de este tipo de encuestas, algunos profesores advirtieron que la satisfacción de los estudiantes hacia el uso de los VRLEs disminuía año tras año. Es decir, estos profesores emplearon una serie de VRLEs como apoyo a sus clases de MSE a lo largo de varios cursos y, tras utilizarlos, los estudiantes respondían encuestas que reflejaban un nivel de satisfacción alto al inicio de la vida útil de estas herramientas didácticas. Sin embargo, a medida que transcurrían los años, el nivel de satisfacción mostrado hacia esos mismos VRLEs disminuía, a pesar de que continuaban siendo herramientas didácticas útiles para el propósito formativo para el cual fueron creadas. Así pues, cuando un docente desarrolla y emplea VRLEs para dar soporte a sus clases de MSE se enfrenta al problema de que la motivación de los estudiantes hacia el uso de estas aplicaciones decae con el paso del tiempo, pudiendo de este modo llegar a disminuir su eficacia formativa.

8. Hipótesis de Trabajo y Objetivos

Con el fin de desarrollar soluciones que solventen o palien los tres problemas descritos en el Apartado 6 se plantean tres hipótesis de trabajo relacionadas con cada uno de ellos. La confirmación de estas hipótesis, que se exponen a continuación, supondría el hallazgo de soluciones totales o parciales a los problemas abordados:

- Hipótesis 1:

  La existencia de uno o varios trabajos que sinteticen cómo se han empleado las RVT en MSE hasta la actualidad facilitaría: (i) la adquisición de ideas que favorezcan el desarrollo de nuevas aplicaciones o actualización de las ya desarrolladas; y (ii) la apertura de nuevas líneas de investigación.
- Hipótesis 2:

  Es posible definir un proceso de desarrollo de los VRLEs destinados a la enseñanza de MSE de modo que los estudiantes alcancen un mayor grado de aprendizaje significativo.
- Hipótesis 3:

  Los VRLEs destinados a dar apoyo a la enseñanza de MSE son aplicaciones informáticas sometidas a las leyes de Lehman, y por tanto es posible que los alumnos mantengan altos niveles de motivación hacia su utilización si son sometidas a trabajos de actualización periódicos.

En base a estas hipótesis, se han definido tres objetivos concretos que se pretenden alcanzar mediante el desarrollo de esta tesis doctoral. La consecución de estos objetivos, que se describen a continuación, permitirá confirmar o refutar las hipótesis de trabajo planteadas:

- Objetivo 1:

  Desarrollar un trabajo que analice y cuantifique el uso de las RVT en el ámbito de la MSE, ampliando el estudio, a partir de los datos obtenidos, y centrado en un ámbito concreto de la MSE que tenga un mayor potencial de interés científico, como por ejemplo el ámbito de la cristalografía.
- Objetivo 2:

Definir un nuevo proceso de desarrollo de VRLEs destinados a dar soporte a la enseñanza de MSE. Este proceso de desarrollo debe perseguir mejorar el aprendizaje significativo con respecto a los VRLEs desarrollados con anterioridad. La evaluación de la mejora en el aprendizaje significativo se llevará a cabo comparando el grado de retención de conocimiento de los estudiantes un año después de haber utilizado cada VRLE.

- Objetivo 3:

  Evaluar en qué medida afecta el paso del tiempo a la valoración que tienen los estudiantes hacia los VRLEs destinados a la enseñanza de MSE, y analizar si puede establecerse una relación con las leyes de Lehman. En base a las conclusiones extraídas, se propondrá una metodología para actualizar los VRLEs de modo que se logre que los estudiantes mantengan un alto nivel de satisfacción hacia su uso con el paso de los años. Este estudio se llevará a cabo analizando diferentes VRLEs desarrollados en diferentes años, midiendo el grado de motivación de los estudiantes hacia su uso.

9. Tecnologías de Realidad-Virtualidad en el Campo de la Ciencia e Ingeniería de Materiales

El concepto de “continuo virtual” fue acuñado para englobar las diferentes RVT, cuyo principal exponente hoy en día son la VR, la AR y la MR. El uso de las RVT ha crecido de manera notable en las últimas décadas, siendo posible encontrar numerosos ejemplos de aplicaciones basadas en estas tecnologías circunscritas al ámbito de la MSE. Cuando se pretende desarrollar un proyecto innovador que involucre el uso de RVT en MSE, resulta de gran utilidad conocer qué trabajos similares se han desarrollado con anterioridad. De este modo los investigadores pueden tener una mayor certeza de que su trabajo será novedoso y pueden adquirir ideas para desarrollar nuevas aplicaciones o actualizar otras que hayan creado con anterioridad.

Con el fin de sintetizar la información relativa a la implementación de las RVT en MSE, en este trabajo se ha llevado una revisión sistemática de literatura científica en la que se expone y analiza un conjunto de trabajos académicos circunscritos a la MSE donde se aborda el uso de estas tecnologías. De los 41 trabajos relevantes analizados en este trabajo de investigación, se ha expuesto brevemente el funcionamiento de las aplicaciones descritas en cada uno de ellos y se ha llevado a cabo un análisis agregado de diferentes parámetros concernientes a dichas aplicaciones. Este estudio ha puesto de manifiesto, entre otros aspectos:

- La mayoría de las aplicaciones se engloban en la categoría de “estructura de materiales, procesado y propiedades”, seguida de lejos por categorías como “computación de materiales y ciencia de datos” o “electrónica, óptica y cuántica”, entre otras. Esto se debe a que la categoría de “estructura, procesado y propiedades de los materiales” incluye un gran número de aplicaciones destinadas a simular ensayos de materiales y a explorar tridimensionalmente redes cristalográficas, que son usos de las RVT que se presentan como evidentes. Por lo tanto, es posible afirmar que actualmente el uso de RVT apenas ha sido estudiado en la mayoría de las áreas de MSE, pudiéndose explorar su uso en áreas en que la idoneidad de utilizar estas tecnologías podría, a primera vista, no resultar evidente.

- La mayoría de las aplicaciones están dirigidas a la docencia y a la investigación. Se ha encontrado un número escaso de ejemplos de aplicaciones destinadas a otros ámbitos, tales como la divulgación y el marketing. El hecho de que la mayoría de las aplicaciones analizadas estén destinadas a la docencia y a la investigación puede tener su origen en que los autores de trabajos académicos publicados suelen desarrollar su actividad profesional en el marco de la universidad. Por ello, es posible afirmar que existen numerosos propósitos para los cuales no se ha estudiado formalmente el uso de las RVT en el ámbito de la MSE, tales como comercio, industria, transporte o construcción, por citar algunos ejemplos, y que para llevar a cabo tales estudios puede resultar conveniente contar con personas que desarrollen una actividad profesional ajena a la universidad.
- La tecnología más empleada es la VR (tanto NIVR como IVR), seguida de lejos por la AR y siendo el uso de la MR testimonial. Llama la atención que la IVR se emplea en mayor medida que la AR, a pesar de que la primera requiere dispositivos específicos (HMDs, controladores y, en muchos casos, ordenadores con alta capacidad de procesamiento gráfico) mientras que la segunda puede ejecutarse en un gran número de teléfonos móviles y tabletas. Esto puede ser debido a que el uso de AR actualmente implica sostener un dispositivo móvil con una mano apuntando su cámara hacia un lugar concreto, a la vez que con la otra mano debe interactuarse a través de su pantalla táctil. Esto conduce a una interactividad pobre si se compara con la interactividad que permite la VR a través de controles, teclado, ratón, etc. Sin embargo, es esperable que a medida que los sistemas de MR reduzcan su precio, esta tecnología ocupe cada vez más parte del espacio que actualmente ocupa la AR ya que, entre otros aspectos, elimina los problemas de interactividad gracias al uso de HMDs y controles similares a los empleados en la IVR.
- En la mayoría de las ocasiones la característica de las RVT que se explota es la posibilidad de interactuar con los objetos virtuales, seguida de la posibilidad de visualizar disposiciones espaciales complejas, siendo la posibilidad de crear

simuladores la menos explotada. Este hecho puede ser debido a que muchos investigadores han encontrado en las RVT un modo sencillo de crear visores de objetos tridimensionales complejos, dotándolos de varias opciones de interactividad. En contraposición, simular mediante RVT máquinas o instalaciones tales como como laboratorios, requiere una mayor inversión de tiempo de creación y conocimientos más amplios de desarrollo.

applied sciences

MDPI

Review

Reality-Virtuality Technologies in the Field of Materials Science and Engineering

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Featured Application: This work offers a global image of the current use of virtual, augmented, and mixed reality in the field of materials science and engineering, constituting a useful means to open new lines of research and explore new uses of these technologies in this field.

Abstract: The increasing use of reality-virtuality technologies (RVTs, which encompass virtual, augmented, and mixed reality) in different fields over the last decade is a phenomenon for which materials science and engineering (MSE) is no exception. To obtain an overview of the implementation of RVTs in MSE, this team conducted a systematic search of the scientific literature published since 2010 addressing the use of RVTs in MSE. Forty-one relevant papers were selected and analyzed in depth to reach several conclusions, including: (i) most of the works (67.3%) are focused on the MSE area of materials structure, processing, and properties, which implies that there are great possibilities for research in other MSE areas; (ii) most of the works (86.8%) are aimed exclusively at education or research, which means that there are many fields outside of the university in which the use of RVT tools has not been developed and evaluated; (iii) the most used technology is virtual reality (85.1%), which means that there are many research possibilities focused on augmented and mixed reality. Researchers can find in the present work examples of the use of RVTs in MSE as well as other relevant information useful to open new lines of research and ideas that can contribute to their current and future work.

Keywords: materials science and engineering; virtuality continuum; virtual reality; augmented reality; mixed reality; education; engineering education; research; spatial visualization; history

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1. Introduction

In 1994, Milgram and Kishino defined the concept of the "virtuality continuum" as the union of the different specific ways in which objects can be displayed according to their real or virtual nature [1]. At one extreme of the virtuality continuum is the representation of the real world, and at the opposite side is a totally virtual world [1]. Between the extremes of the virtuality continuum are different representations of the environment that differ from each other depending on the degree of reality or virtuality used and how both types of representation are intertwined [1]. Based on this, currently it can be found that there are three reality-virtuality technologies (RVTs) that are most commonly used: virtual reality (VR), augmented reality (AR), and mixed reality (MR) [2].

VR allows users to interact in three dimensions with virtual environments generated by computers [3], being able to experience a world beyond the real one [4]. The concept of VR originated from the work of Ivan Sutherland in 1965 when he published his essay entitled "The Ultimate Display" [5]. Sutherland [5] described a device that shows the user images of a virtual environment in addition to transmitting information to other parts such as the ears or hands [4]. Since then, the term VR has been used to define different systems and applications, both at the software and hardware level [6]. Within VR, it is common to differentiate non-immersive VR from immersive VR [6,7]. In the first case (non-immersive VR), the virtual environments are shown through a screen. Examples of non-immersive VR would be the virtual worlds such as Second Life [8] or most of the current 3D video games for video game consoles. In the second case (immersive VR), the aim is to create the sensory illusion of being completely present, immersed, in the virtual environment [9]. Examples of immersive VR would be the CAVE-type systems [6,10] or those in which head-mounted displays (HMDs) are used [6].

AR allows real-time visualization of the real physical world "augmented" thanks to the inclusion of information and virtual elements generated by the computer [11]. In this type of technology, real elements and virtual elements are combined [11]. The term AR was coined in 1992 by Boeing researchers Caudell and Mizell [12] when they described a system that allowed virtual information to be superimposed on a worker's field of vision to improve efficiency in the performance of manufacturing activities [13]. Currently, the use of AR technology is mainly linked to smartphones and tablets (as would be the case of the Pokémon Go game [14]), and to HMDs [7,15,16].

MR, as defined by Milgram and Kishino in 1994 [1], is conceptually close to AR, since both technologies combine real and virtual elements. However, MR implies not only the superimposition of virtual elements on a real environment as occurs with AR, but also these virtual elements must be indistinguishable from the physical world [17]. When using MR, virtual elements must be integrated into the physical world [16] and, therefore, visual coherence plays a decisive role in this type of technology [18]. MR allows users to interact in real-time with both real and virtual elements, with real elements being able to modify virtual elements [17]. As an example, if we imagine a virtual box under a table, a user using MR will not be able to see it until he/she crouches down and look under the table; on the contrary, a user using AR will always see the box superimposed on the table, without the need to bend down [17]. Nowadays, the main commercial system that allows MR to be implemented is Microsoft HoloLens [17,18]. The display device of Microsoft HoloLens is an HMD of the optical see-through type, which mixes real and virtual elements through an optical combiner located in the user's visual path [18].

The use of RVTs in the field of engineering in recent decades has experienced notable and continuous growth. This fact can be deduced from analyzing the number of academic papers published since 2001 that refer to these technologies [15,19]. Materials science and engineering (MSE) is a field in which numerous examples of applications based on RVTs have been developed with the purpose of giving support to the teaching-learning process [15,20,21]. One of the reasons that have driven this expansion of the use of RVTs in MSE training lies in the possibilities that VR and AR (and, more recently, also MR) offer when creating applications that [20]: (i) facilitate spatial vision (that is, allow the user to visualize three-dimensional shapes or arrangements that may be complex to understand); (ii) allow users to interact with virtual elements, both those that represent real and tangible objects as well as those that represent abstract concepts (e.g., three-dimensional diagrams [22]) or intangible realities (e.g., representations of crystal structures at the atomic level [23]); and (iii) simulate the operation of real devices or installations, such as machines, tools or entire laboratories [24].

On the other hand, as Lehman [25–28] pointed out, the development of computer programs must be associated with a plan for constantly updating and adapting to current technology, environment and tastes. This updating process shall be performed both at the software and hardware levels, to avoid the phenomenon of technological obsolescence. Avoiding technological obsolescence helps to prevent computer applications from being perceived as obsolete by users and their use becoming unsatisfactory. The study by Vergara et al. [29] found that this fact is applicable to any application based on RVTs focused on improving MSE teaching. Therefore, it is possible to conclude that it is of great importance to know what technologies are used and how they are currently implemented in the field of MSE when trying to develop or update a tool based on reality-virtuality.

When an individual intends to carry out an innovative project that uses VR, AR, or MR in the field of MSE, it can be very useful to know what similar works have been developed before and to have an image of the current state of the art. In this way, the researchers can ensure that his/her new work will be innovative, and he/she will also be able to acquire ideas to develop new reality-virtuality tools or update others that he/she has previously developed to minimize the effects of technological obsolescence. In this sense, works such as that of Extremera et al. [23] offer a perspective of the use of VR and AR in crystallography, which is encompassed in the field of MSE corresponding to the areas of "materials structure, processing, and properties". However, the authors have not found any work that offers a global overview of the use of RVTs in the field of MSE.

In this review, a systematic search is carried out on three different web platforms (Web of Science, Scopus, and IEEE Xplore), which leads to the selection of 41 relevant works published since 2010. Each of the 41 selected works is briefly described and classified according to different parameters, subsequently analyzing the data extracted from such classifications in an aggregated manner. As a result of this work, a researcher interested in creating or developing a tool based on reality-virtuality applied to MSE can learn about: (i) particular examples of use; (ii) which areas of MSE are the most addressed; (iii) what purposes are pursued by the created tools; (iv) what particular technologies are used (immersive VR, non-immersive VR, AR, or MR); and (iv) what characteristics of the RVTs are exploited (improvement of spatial vision, interactivity with virtual elements or simulation of real devices or installations). It is hoped that this information will help researchers to reveal areas of MSE for which RVT-based tools have not yet been developed, to elucidate new purposes that have not been explored before, and to identify works that can inspire their development at the technological level.

2. Methodology

The development of the systematic search was carried out using a methodology based on previous works [30–32], which consisted of three main stages: planning, development, and report. Each of these stages are described in the following subsections.

2.1. Planning

During the planning stage, the motivation, objectives, and research questions of the systematic search were defined. The motivation for this systematic search arose from the need to have a global image of how RVTs are used in the field of MSE. Obtaining this impression through the scientific works published in the last decade, it is possible to favor the opening of new lines of research that allow the development of new tools based on RVTs (or updating the existing ones), which can be used in new fields and with purposes other than those pursued to date, in addition to facilitating the choice of technology to be used. To meet this need, three main objectives were established that must be achieved. First, the aim was to have a list of relevant works in which the general operation of the tools was briefly described. Second, we intended to discover the magnitude of the number of academic papers in which the use of RVTs is linked to MSE, as well as their typology (e.g., conference papers), and what proportion of these papers includes some type of empirical study. Third, we sought to find out to which areas of MSE the tools developed in the academic field are circumscribed and to which sectors (e.g., education) they are directed. Fourth, we sought to discover the degree of implementation of the different types of RVTs and what properties have been exploited and reported to date.

To achieve the three established objectives, this systematic search aimed to answer the following questions:

1. How do RVT-based tools work and what specific purpose do they pursue?
2. How many scientific works have been published in the last decade explicitly relating to RVTs and MSE, and have they been indexed in Web of Science, Scopus, or IEEE Xplore?

3. In what type of document have these works been published—that is, how many have been published in the form of articles, conference papers, reviews, or book chapters, and how many contain an empirical study (empirical data collection and analysis thereof)?
4. In which areas of MSE are the described tools circumscribed?
5. To which sectors are the described tools directed?
6. What types of RVTs are used in the described tools—that is, how many use immersive VR, non-immersive VR, AR, or MR?
7. What properties of the RVTs are exploited in the described tools—that is, how many exploit the improvement of spatial vision, the possibility of interacting with virtual elements, or the simulation of real gadgets?

2.2. Development

During this stage, the search strategy and the criteria for the inclusion and exclusion of works were defined, based on which the search was carried out on the different web platforms and the relevant works were selected.

2.2.1. Search Strategy

The search strategy used sought to identify those works in which the use of RVTs has been explicitly related to MSE. For this reason, the search inquiries were formulated following the basic structure shown in Table 1, through which we sought to obtain results that contain one or several of the terms of Search Group 1 (terms referring to RVTs) and one or several of the terms in Search Group 2 (terms related to MSE).

Table 1. The basic structure of the search strings. The search shall return results with one or more of the terms contained in Search Group 1 and one or more terms contained in Search Group 2.

Search Group 1	Logical Operator	Search Group 2
virtual reality augmented reality mixed reality	AND	materials science materials engineering materials science and engineering materials characterization materials testing

2.2.2. Inclusion and Exclusion Criteria

The application of the inclusion and exclusion criteria is shown in Table 2 and based on them, only those search results that allow us to answer the 7 research questions raised in the Section 2.1 were selected.

Table 2. Inclusion and exclusion criteria that were followed to select relevant results.

Inclusion Criteria	Exclusion Criteria
Works where the use of RVTs in MSE is described. Works published between 2010 and 2021. Results related to articles, conference papers, reviews, or book chapters. Results written in English.	Works where there is not a direct relationship between the use of RVTs and MSE. Works published before 2010. Results related to information about conferences [1]. Results written in a different language than English. Duplicate results.

[1] Searches in Scopus often return several results that are only information about conferences (title, date, etc.), but these results are not linked to any specific academic work.

2.2.3. Execution of the Search and Selection of Relevant Results

The search was carried out on three different web platforms: Web of Science, Scopus, and IEEE Xplore. In each of these web platforms, the search was performed using a specific search inquiry for each of them (Table 3) based on the structure defined in Table 1. Note that the Web of Science search was carried out through all the databases available on this platform. This search was conducted on 24 July 2021, and the results obtained were refined by language (all works written in a language other than English were discarded), by time range (all works published before the year 2010 were discarded), and by type of result (all results that were not articles, proceedings papers, reviews or book chapters were discarded). The number of documents obtained in this manner was 269, of which 31 corresponded to Web of Science, 184 to Scopus, and 54 to IEEE Xplore. Subsequently, from this set of results (269) duplicate results (29) were eliminated, leaving 240 unique results. Each of these 240 documents was analyzed individually (through its abstract or its abstract and full text together) to determine its eligibility, discarding those that did not relate the use of VR, AR, or MR with MSE. In this way, 41 works were selected, which were subsequently analyzed in detail and described in this work. The job search and selection process are outlined in Figure 1.

Table 3. Search string used on each search web platform.

Search Platform	Search String
Web of Science	TS = ((“virtual reality” OR “augmented reality” OR “mixed reality”) AND (“materials science” OR “materials engineering” OR “materials science and engineering” OR “materials characterization” OR “materials testing”))
Scopus	TITLE-ABS-KEY((“virtual reality” OR “augmented reality” OR “mixed reality”) AND (“materials science” OR “materials engineering” OR “materials science and engineering” OR “materials characterization” OR “materials testing”))
IEEE Xplore	(“All Metadata”:”virtual reality” OR “augmented reality” OR “mixed reality”) AND (“All Metadata”:”materials science” OR “materials engineering” OR “materials science and engineering” OR “materials characterization” OR “materials testing”)

2.3. Report

The development of the report (which corresponds to the section below entitled “3. Results”) exposed the information obtained through the analysis of the 41 selected relevant works. To obtain answers to the 7 research questions raised in subsection “2.1. Planning”, the results obtained from the analysis were exposed according to the scheme proposed by the research questions:

- Features of the applications exposed in the selected works and their descriptions.
- Analysis of the number and types of documents selected;
- Analysis of the areas of MSE in which the applications described in the selected works are circumscribed;
- Analysis of the sectors to which the applications described in the selected works are directed;
- Analysis of the particular types of RVTs used in the applications described in the selected works;
- Analysis of the properties of the RVTs that are exploited in the selected works.

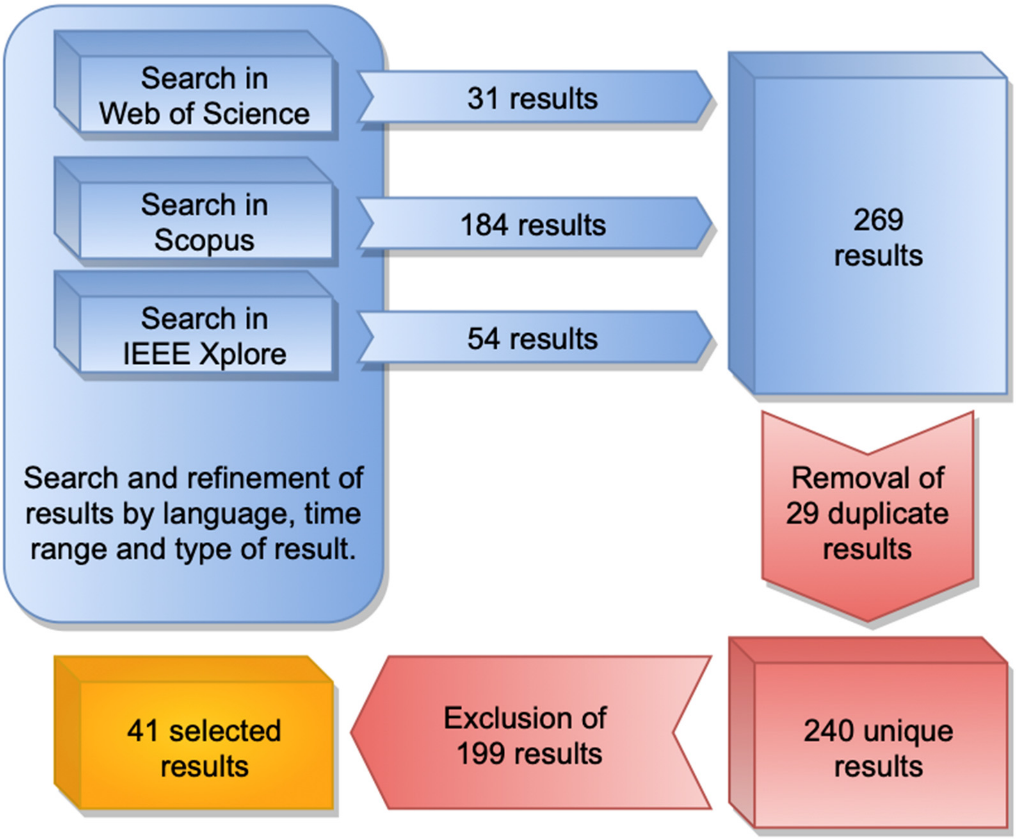

Figure 1. Illustrative diagram of the process followed for the selection of works.

3. Results

3.1. Features of the Applications and Description

Table 4 lists the analyzed works arranged by year of publication and summarizes the features associated with each of them: (i) year of publication, (ii) type of document, (iii) inclusion of an empirical study, (iv) scope of MSE in which the application is circumscribed, (v) sector to which it is directed, (vi) type of RVT used and (vii) its properties that are exploited. Figures 2–4 are Venn diagrams that show the classification of the described applications according to MSE areas where they are circumscribed, their target sectors and the type of RVTs that they employ, respectively.

Note that, in this work, only those that employ some kind of HMD or CAVE-type system were considered as immersive VR-based applications. This led to us classifying certain VR-based applications as non-immersive, even if they offer a partially immersive experience (as occurs, for example, when using a 3D TV combined with stereoscopic glasses). In addition, an application was determined to have interactivity when the user can interact with virtual objects (e.g., by rotating or moving them). Finally, a simulation property was established when applications simulate or mimic a real apparatus or facility (e.g., a hardness tester or a test laboratory).

Table 4. Summary of the features of the 41 analyzed works. Note that the following nomenclature was used exclusively in this table: non-immersive virtual reality (NIVR), immersive VR (IVR).

Work Number	Reference	Year	Document Type	Study Included	MSE Scope	Target Sectors	RVT Used	RVT Properties
1	[33]	2010	Conference paper	No	Materials structure, processing, and properties	Not specified	NIVR	Interactivity Simulation
2	[34]	2011	Conference paper	No	Materials structure, processing, and properties	Education Research	NIVR	Spatial vision Interactivity
3	[35]	2011	Conference paper	No	Materials computing and data science	Research	NIVR	Spatial vision Interactivity
4	[36]	2012	Conference paper	Yes	Materials structure, processing, and properties	Research	NIVR	Spatial vision Interactivity
5	[37]	2012	Conference paper	No	Biomaterials and soft materials	Not specified	NIVR	Interactivity Simulation
6	[38]	2013	Article	Yes	Materials structure, processing, and properties	Education	NIVR	Interactivity Simulation
7	[39]	2013	Conference paper	No	Materials structure, processing, and properties Material characterization	Education	NIVR	Interactivity Simulation
8	[40]	2014	Article	No	Materials structure, processing, and properties	Education Research	NIVR	Spatial vision Interactivity
9	[41]	2014	Conference paper	No	Structural and functional materials	Education Research	NIVR	Spatial vision
10	[42]	2015	Conference paper	No	Materials structure, processing, and properties Electronics, optics and quantum	Research	IVR	Spatial vision Interactivity
11	[43]	2015	Conference paper	No	Materials structure, processing, and properties	Research	NIVR	Spatial vision Interactivity
12	[44]	2016	Article	Yes	Materials structure, processing, and properties Energy and sustainability	Education	NIVR AR	Spatial vision Interactivity Simulation
13	[45]	2017	Article	Yes	Materials structure, processing, and properties	Education	NIVR	Interactivity Simulation
14	[46]	2015	Book chapter	Yes	Materials structure, processing, and properties	Education	NIVR	Interactivity Simulation
15	[47]	2017	Conference paper	No	Materials structure, processing, and properties	Education	IVR	Interactivity Simulation

Table 4. *Cont.*

Work Number	Reference	Year	Document Type	Study Included	MSE Scope	Target Sectors	RVT Used	RVT Properties
16	[48]	2017	Conference paper	Yes	Materials structure, processing, and properties Materials computing and data science	Education Research Outreach Marketing	IVR	Spatial vision Interactivity
17	[49]	2017	Conference paper	No	Carbon-based nanocomposite materials and applications	Not specified	IVR NIVR	Spatial vision Interactivity
18	[50]	2018	Conference paper	No	Materials structure, processing, and properties	Research	NIVR	Spatial vision Interactivity
19	[51]	2018	Conference paper	Yes	Materials structure, processing, and properties	Education	IVR	Spatial vision Interactivity
20	[52]	2018	Conference paper	Yes	Materials characterization	Education Research	IVR NIVR	Spatial vision Interactivity
21	[53]	2018	Conference paper	Yes	Materials structure, processing, and properties	Education	IVR NIVR	Interactivity Simulation
22	[54]	2018	Conference paper	Yes	Materials structure, processing, and properties	Education	MR	Spatial vision Interactivity
23	[55]	2019	Conference paper	Yes	Carbon-based nanocomposite materials and applications Materials computing and data science	Education Research	IVR AR	Spatial vision Interactivity
24	[56]	2019	Article	Yes	Materials structure, processing, and properties	Education	IVR NIVR	Spatial vision Interactivity Simulation
25	[57]	2019	Conference paper	No	Materials structure, processing, and properties	Education Research	IVR	Spatial vision Interactivity
26	[58]	2019	Article	Yes	Materials structure, processing, and properties	Education	IVR NIVR	Spatial vision Interactivity
27	[59]	2019	Conference paper	Yes	Materials structure, processing, and properties	Education	NIVR	Interactivity Simulation
28	[20]	2019	Article	Yes	Materials structure, processing, and properties	Education	NIVR	Spatial vision Interactivity Simulation
29	[60]	2019	Article	No	Materials structure, processing, and properties Materials computing and data science	Education Research Outreach Marketing	IVR	Spatial vision Interactivity

Table 4. *Cont.*

Work Number	Reference	Year	Document Type	Study Included	MSE Scope	Target Sectors	RVT Used	RVT Properties
30	[61]	2019	Conference paper	Yes	Materials structure, processing, and properties	Education	IVR NIVR	Spatial vision Interactivity
31	[62]	2019	Article	Yes	Materials computing and data science	Research	IVR	Spatial vision Interactivity
32	[63]	2019	Conference paper	No	Materials structure, processing, and properties	Education	NIVR	Interactivity Simulation
33	[64]	2020	Conference paper	Yes	Materials structure, processing, and properties	Education	IVR NIVR	Spatial vision Interactivity Simulation
34	[65]	2020	Conference paper	Yes	Electronics, optics and quantum	Education	IVR	Spatial vision
35	[66]	2020	Article	Yes	Materials structure, processing, and properties	Education	AR	Spatial vision Interactivity
36	[67]	2020	Conference paper	Yes	Materials structure, processing, and properties	Education	NIVR AR	Spatial vision Interactivity
37	[29]	2020	Article	Yes	Materials structure, processing, and properties	Education	NIVR	Spatial vision Interactivity
38	[68]	2020	Article	Yes	Materials structure, processing, and properties	Research	IVR	Interactivity Simulation
39	[69]	2020	Conference paper	Yes	Materials structure, processing, and properties Electronics, optics and quantum	Education	IVR AR	Spatial vision Interactivity Simulation
40	[70]	2020	Article	Yes	Materials structure, processing, and properties	Education	IVR AR	Interactivity Simulation
41	[71]	2021	Conference paper	No	Materials structure, processing, and properties Electronics, optics and quantum	Education	IVR AR	Spatial vision Interactivity Simulation

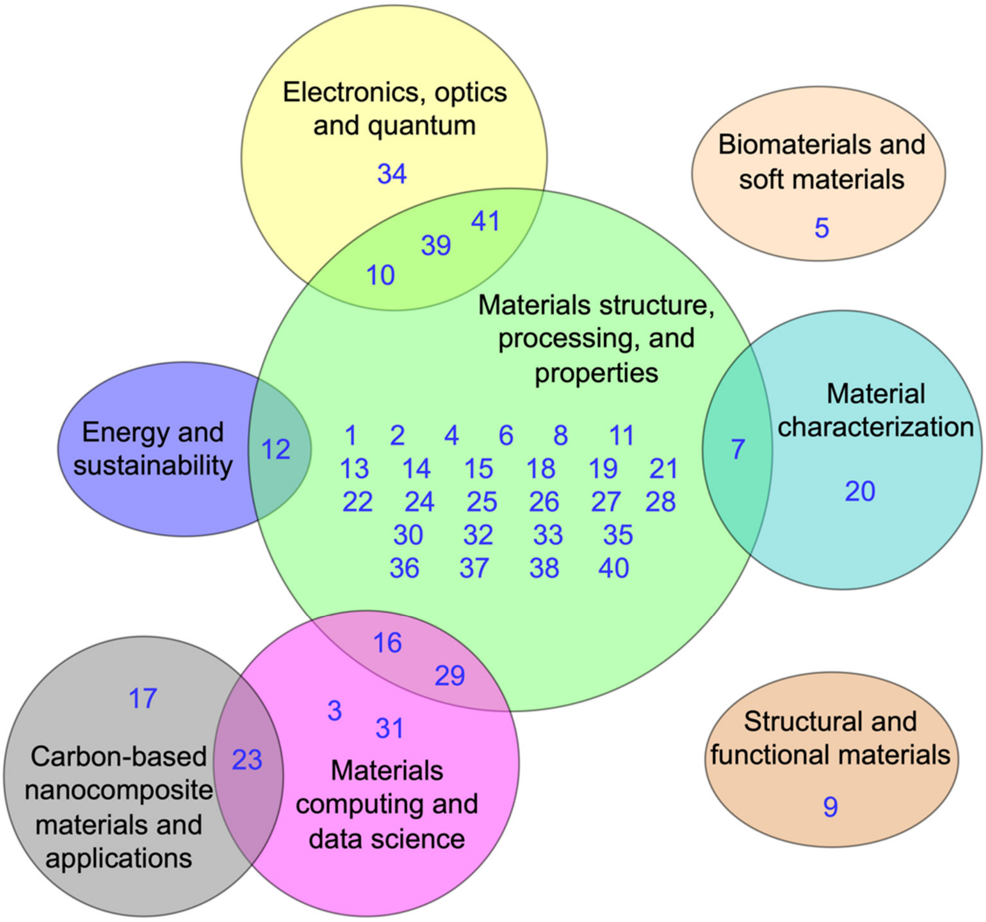

Figure 2. Area of MSE in which described applications are circumscribed. Numbers 1 to 41 identify the works listed in Table 4 (column "Work Number").

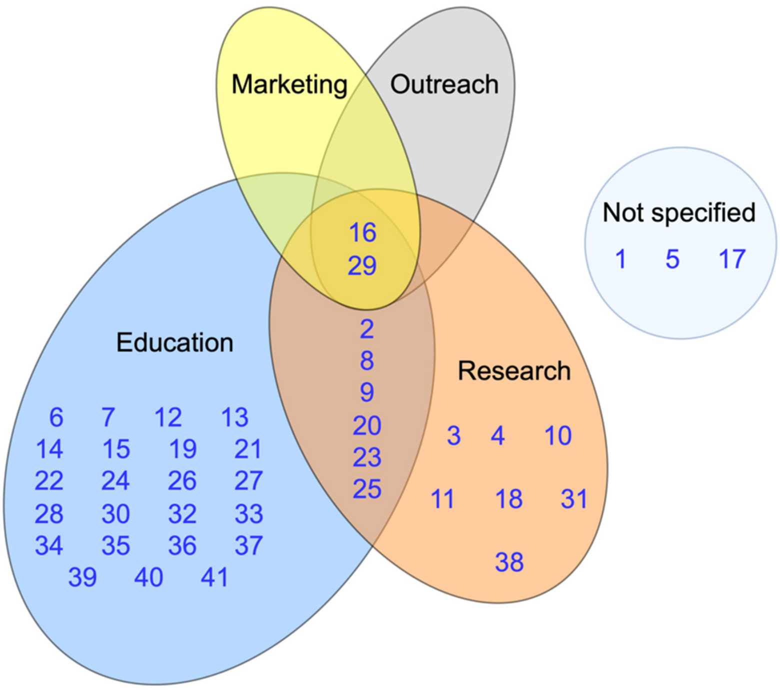

Figure 3. Target sector of the described applications. Numbers 1 to 41 identify the works listed in Table 4 (column "Work Number").

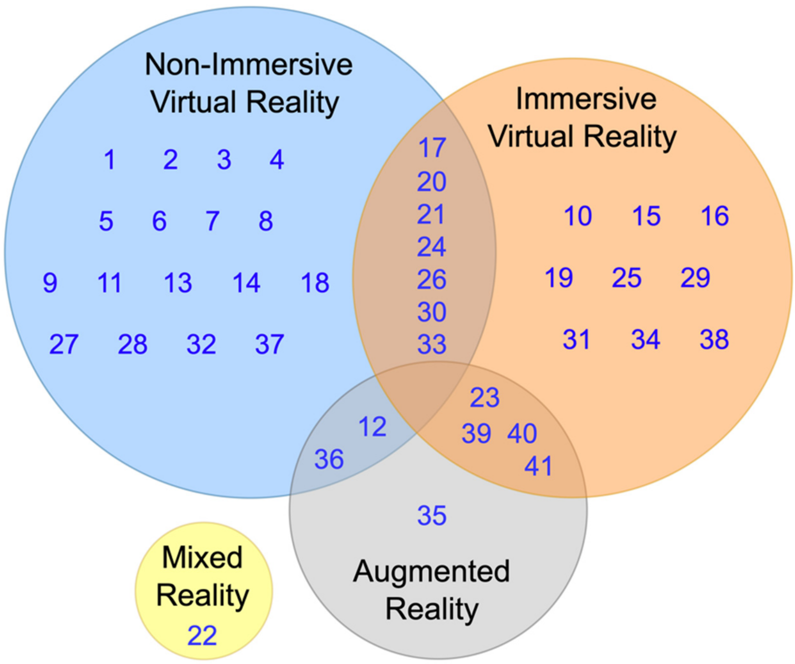

Figure 4. RVTs employed by the described applications. Numbers 1 to 41 identify the works listed in Table 4 (column "Work Number").

The following is a summary description of the applications exposed in each of the 41 selected works, highlighting those aspects that the authors have considered most relevant. The following arrangement matches with Table 4 (i.e., year of publication):

- Work 1: *VRML-Based Laboratory System for Material Mechanical Performance Testing* [33]

Tang and Wu presented a virtual laboratory aimed at simulating different material mechanical performance tests. In this virtual laboratory, the user can interact with different 3D machines and tools to simulate different tests such as tensile, compression, fatigue, impact, and creep deformation.

- Work 2: *The Emergence of Immersive Low-Cost 3D Virtual Reality Environments for Interactive Learning in Materials Science and Engineering* [34]

Doblack et al. reported a system called IDEAS that seeks to facilitate the understanding of nanostructures through a 3D television, which is displayed using stereoscopic glasses to achieve the sensation that the images shown have volume. The virtual system uses several devices (infrared cameras, tracing system, etc.), dedicated software called the Nanotech Construction Kit, and accelerated simulation capabilities to give the user an immersive experience being used for research and learning. For instance, the IDEAS system allows the user to create and manipulate atomic structures of nanomaterials in 3D (e.g., nanotubes), as well as visualize models resulting from molecular dynamics simulations.

- Work 3: *X3DMMS: An X3DOM Tool for Molecular and Material Sciences* [35]

Zollo et al. reported a web application in which the user can visualize and manipulate 3D models of virtual complex molecular systems to define the initial configuration parameters of their interactions. Subsequently, the user can obtain a file directly from this web application that can be entered into a molecular simulation program.

- Work 4: *A Simultaneous 2D/3D Autostereo Workstation* [36]

Chau et al. described a system that has a dynamic parallax barrier display that allows users to simultaneously view 3D virtual models and 2D windows of office applications on the same screen. In this work, the authors use this system to visualize in three dimensions (giving the user a sense of depth without the need to use stereoscopic glasses) the atomic structure of different materials, as well as to interact with these models through a touchscreen or different peripherals (such as controllers).

- Work 5: *Real-Time 3D Visualization in an Open Architecture of a Robotic Application in the Biomechanics* [37]

Martinez et al. described a method aimed at analyzing, through VR, biomechanical tests carried out by a robot arm with 6 degrees of freedom. This method allows for programming a certain test and visualizing it in a virtual 3D model of the robot and the sample of biological material tested. On the one hand, this system gives the possibility of viewing the experiment from different perspectives before carrying it out using the real robot to verify that the programmed test procedure is correct and, on the other hand, it allows for viewing, through the virtual model, the behavior of the real robot while the real test is being carried out, thus offering better viewing perspectives and minimizing the need to be close to the real robot when it is running.

- Work 6: *Haptic System for Determining the Young Modulus of Materials* [38]

Restivo et al. reported a non-immersive VR-based application that simulates a bending test. This application uses a haptic device that allows the user to physically notice the force that is being exerted to bend the tested virtual specimen.

- Work 7: *Transforming Undergraduate Engineering Education with 3D Virtual Reality Laboratory* [39]

Ari-Gur et al. presented a set of virtual laboratories made of various educational modules. These virtual labs allow students to simulate, in a 3D environment, experiments related to X-ray diffraction, scanning electron microscopy, heat treatment of various alloyed metals, and different mechanical tests on concrete and asphalt.

- Work 8: *Novel 3D/VR Interactive Environment for MD Simulations, Visualization and Analysis* [40]

Doblack et al. described an application aimed at facilitating the understanding of nanostructures. This application is executed using a 3D VR interactive environment with high-performance simulation capabilities, and the user sees the virtual objects on a 3D high-definition (HD) television combined with stereoscopic glasses. This application allows the user to create and manipulate nanostructures (e.g., wires, helices) and simulate their structural transformation using an open-source molecular dynamics program (LAMMPS). In addition, the user can interact with the virtual 3D models and configure different simulation parameters via a simulator (LAMMPS) and MATLAB code for analysis.

- Work 9: *Virtual Reality Visualization for Short Fibre Orientation Analysis* [41]

Pastorelli and Hermann presented a methodology that allows the automated analysis of fiber orientations in short fiber-reinforced composites to be carried out. After scanning a sample of steel fiber reinforced concrete, the algorithm described analyzes the distribution of its fibers within the concrete matrix. From the data generated during this analysis, images were generated that show the fibers, which are projected on three surfaces arranged orthogonally to each other to be visualized in three dimensions using stereoscopic glasses, thus achieving a certain degree of immersion in the virtual environment.

- Work 10: *Immersive Visualization for Materials Science Data Analysis Using the Oculus Rift* [42]

Drouhard et al. reported a methodology that allows the exploratory visualization of data sets of large crystal structures and neutron scattering, using an HMD. The described project aims to enable researchers to carry out the analysis of data sets in an immersive visualization environment in an agile and intuitive way.

- Work 11: *Incorporating D3.js Information Visualization into Immersive Virtual Environments* [43]

Griffin et al. reported a virtual environment in which the microstructure of cement pastes and concrete can be visualized and analyzed (using 3D and 2D models) during the hydration or degradation processes.

- Work 12: *Beyond the Flipped Classroom: A Highly Interactive Cloud-Classroom (HIC) Embedded into Basic Materials Science Courses* [44]

Liou et al. presented an application composed of two educational modules. The first module, which uses AR, allows the student to visualize unit cells in 3D when pointing the camera of their mobile device at certain 2D images of them. The user can rotate these 3D figures to see them from different angles, as well as touch them to obtain more information or view animations. The second module uses non-immersive VR to allow the student to view and interact with a 3D virtual car equipped with a fuel cell. This module allows the student to learn about the operating principle of fuel cells and their use in a car.

- Work 13: *New Approach for the Teaching of Concrete Compression Tests in Large Groups of Engineering Students* [45]

Vergara et al. described the classroom application of a 3D virtual laboratory based on [72] in which the user can simulate performing a compression test on different concrete specimens. The user has the possibility of moving around in the laboratory and to interact with the different parts of the testing machine to carry out the different actions that are required to carry out in that test.

- Work 14: *Virtual Environments in Materials Science and Engineering: The students' opinion* [46]

Vergara et al. described two 3D virtual laboratories intended to simulate materials testing. In the first case, students can carry out a tensile test, while in the second case, they can perform a concrete compression test.

- Work 15: *Virtual Lab for Material Testing Using the Oculus Rift* [47]

Ortelt and Ruider reported a 3D virtual laboratory designed to simulate the performance of a uniaxial tensile test or a cupping test. In addition, the user can interact with the virtual 3D models, configure different test parameters, and hide parts of the machine to observe the deformation of the specimens in details.

- Work 16: *Virtual Reality Toolset for Material Science: NOMAD VR Tools* [48]

García-Hernández and Kranzlmüller presented a suite of immersive VR programs whose purpose is to visualize the evolution of chemical simulations and explore atomic structures. Datasets (from the NOMAD repository [73] or created by the user) containing information regarding atomic structures and simulations are introduced in these programs to be processed and thus be visualized through an HMD or a CAVE system.

- Work 17: *Visualization of Higher Genus Carbon Nanomaterials: Free Energy, Persistent Current, and Entanglement Entropy* [49]

Duong and McGuigan described a procedure that aims to explore carbon nanomaterials and some of their chemical and electrical properties. The procedure described in this work allows, through 3D modeling and programming, to visualize in 3D the atomic structure of nanomaterials (such as double rings or nanotorus) and a graphic representation of some of their properties such as free energy, persistent current or entanglement entropy.

- Work 18: *A Virtual Reality Visualization Tool for Three-Dimensional Biomedical Nanostructures* [50]

Pajorová et al. reported a procedure that consists of scanning synthetic polymeric nanofibrous membranes with a scanning electron microscope and subsequently obtaining a 3D model of them. This 3D model can then be viewed using VR to facilitate analysis of the structural properties of these membranes. In this way, the porosity, density, and average diameters of each fiber of nanofibrous membranes can be analyzed more accurately and the mechanical properties of the material can be better described from the point of view of the cell–materials interactions. This paper shows that this procedure was used in the manufacturing process of the skin substitute.

- Work 19: *Can Virtual Reality Enhance Learning: A Case Study in Materials Science* [51]

Caro et al. presented a methodology that allows students to make drawings on 3D models of atomic arrangements to learn concepts related to crystallographic networks (particularly the structure of fundamental unit cells such as body-centered cubic or face-centered cubic) using immersive VR.

- Work 20: *Evaluation of Scientific Workflow Effectiveness for a Distributed Multi-User Multi-Platform Support System for Collaborative Visualization* [52]

Banic et al. reported a collaborative system that allows various users who are in different locations to simultaneously view the same set of virtual objects. Additionally, users may display these using different systems (e.g., during a given co-viewing session, one user may use an HMD while another may use a CAVE system). This paper describes the use of this system to visualize and analyze a graphite billet.

- Work 21: *Remote and Virtual Labs for Engineering Education 4.0: Achievements of the ELLI Project at the TU Dortmund University* [53]

Grodotzki et al. presented a virtual laboratory through which students can learn about different material tests, such as tensile or cupping tests. This virtual laboratory allows access to a 3D environment that recreates a room in which material tests are carried out. In it, the user must configure the test parameters to view a pre-run associated finite element method (FEM) simulation. In addition, the user can visualize pre-run FEM simulations, isolated from any environment or machine, corresponding to different tensile tests, using a mobile device or an HMD.

- Work 22: *Use of Mixed Reality Tools in Introductory Materials Science Courses* [54]

Mansoor et al. reported an application that uses MR to facilitate the teaching of crystallography. Using Holo Lens glasses, the user can explore MR 3D models of unit cells using different viewing options, either by moving himself around the room and orienting his face towards the virtual position occupied by each network (which is displayed on the real scenario in which the user finds himself) or by rotating the crystallographic networks themselves. In addition, the application has a module that allows the user to represent crystallographic planes by entering Miller indices.

- Work 23: *A Framework for Visualizing the Dynamic Events of Carbon Nanocomposites Using Virtual and Augmented Reality Tools* [55]

Iqbal et al. presented a framework that uses VR and AR to make it easier for users to visualize and understand simulations involving nanocomposites. This work describes an application of this framework that allows visualizing how carbon-nanocomposites react during oxidation. To do this, users can upload the data of a certain reaction and view it through VR or AR on a wide range of devices. In addition, these simulations can be viewed individually or shared with other users to view them simultaneously.

- Work 24: *Application of Virtual Reality for Learning the Material Properties of Shape Memory Alloys* [56]

Tarng et al. reported an application that allows students to carry out an interactive virtual experiment that involves the deformation, heat treatment, and recovery of the original shape of a shape memory allow type material. During the realization of the virtual experiment, the student can observe the changes that take place in its crystalline structure. Additionally, the application allows the user to learn interactively about two real-life applications of this type of material, as well as complete a test to evaluate the knowledge acquired.

- Work 25: *Crystal VR: Creating an Immersive Scientific Tool for Learning and Research* [57]

Greenwald et al. presented an application that allows visual analysis of crystallographic structures. Through this application, the user can choose one of the crystallographic structures present in a database to explore it using different display options, as well as analyze its symmetries.

- Work 26: *CrystalWalk: An Educational Interactive Software for Synthesis and Visualization of Crystal Structures* [58]

Bardella et al. reported an application based on immersive VR or non-immersive VR that allows the user to learn concepts related to crystallographic structures. The user can configure unit cells and view them using different display options, as well as perform operations such as creating plans and directions from its Miller indices.

- Work 27: *Design of Virtual Reality Learning Environments: Step-by-Step Guidance* [59]

Extremera et al. described a virtual laboratory that allows students to carry out a hardness test in a virtual experiment using non-immersive VR. The user of the application is guided step by step in performing the experiment, which consists of measuring the Rockwell hardness (on scale B or C) of a metal specimen.

- Work 28: *Meaningful Learning Through Virtual Reality Learning Environments: A Case Study in Materials Engineering* [20]

Vergara et al. described a methodology to create VR learning environments aimed at supporting the teaching of material testing and crystallography. It is noteworthy that the exposed platforms are aimed at simulating material tests in virtual laboratories (both destructive and non-destructive) and at visualizing Bravais networks.

- Work 29: *NOMAD VR: Multiplatform Virtual Reality Viewer for Chemistry Simulations* [60]

García-Hernández and Kranzlmüller described a set of programs that use immersive VR to show the user how chemical simulations evolve, as well as allowing them to explore atomic structures. The user can create datasets or import them from the NOMAD repository [73] to view them through an HMD or a CAVE type system.

- Work 30: *Spatial Comprehension of Crystal Lattices Through Virtual Reality Applications* [61]

Vergara et al. reported an application that aims to facilitate the teaching of Bravais networks. When the user starts the application, he or she is allowed to visit a virtual museum, in one of whose rooms the 14 Bravais nets are exhibited. The user can zoom in on any of them to rotate it, view directions and crystallographic planes, etc.

- Work 31: *Study of Commodity VR for Computational Material Sciences* [62]

Hagita et al. reported a study focused on the use of immersive VR to visualize atomic structures and molecular dynamics simulations. This study evaluates the performance of the VR system based on the type of data displayed.

- Work 32: *Virtual Reality Learning Environments in Materials Engineering: Rockwell Hardness Test* [63]

Rubio et al. presented an application aimed at facilitating the learning of hardness tests. This application simulates a 3D laboratory in which there is a hardness tester that allows for carrying out a hardness test on two different Rockwell scales.

- Work 33: *Effects of Time in Virtual Reality Learning Environments Linked with Materials Science and Engineering* [64]

Extremera et al. reported a paper that describes the methodology for creating learning environments based on immersive and non-immersive VR, the purpose of which is to facilitate the teaching of materials testing and crystallography concepts. This work focuses on analyzing the design process of educational platforms and their obsolescence with their educational effectiveness.

- Work 34: *How Can Instructors Strengthen Students' Motivation to Learn Complex 3D Concepts in an Engineering Classroom?* [65]

Batra et al. described a work that investigated the influence of VR on the motivation in students during a class in which they are taught concepts related to excitons. During this class, students viewed 3D animations through the YouTube app in "VR mode" running on smartphones coupled with low-cost HMDs (Google Cardboard). In this way, the students could visualize the animated 3D models from different angles simply by moving their heads.

- Work 35: *Imparting Materials Science Knowledge in the Field of the Crystal Structure of Metals in Times of Online Teaching: A Novel Online Laboratory Teaching Concept with an Augmented Reality Application* [66]

Müssig et al. described an AR-based application usable on smartphones, which aims to facilitate the understanding of crystallographic networks. This app visualizes crystallographic networks (created by the user or the app developers) from different angles, as well as explores interatomic distances or defects.

- Work 36: *Implementing Interactive 3-D Models in an Entry Level Engineering Course to Enhance Students' Visualization* [67]

Hain and Motaref proposed a methodology to visualize 3D objects that allow understanding concepts related to the mechanics of materials. This methodology is based on using the Sketchfab platform so that teachers can upload three-dimensional models and students can view them through the app associated with the said platform using non-immersive VR or AR.

- Work 37: *The Technological Obsolescence of Virtual Reality Learning Environments* [29]

Vergara et al. presented two applications aimed at improving the understanding of ternary phase diagrams [22,74], on the one hand, and Bravais networks [23,75] on the other. The first application allows the user to view a 3D ternary phase diagram and explore each of the component phases. The second application allows the user to explore a three-dimensional model of each of the Bravais networks.

- Work 38: *Toward "on-Demand" Materials Synthesis and Scientific Discovery Through Intelligent Robots* [68]

Li et al. reported a robotics intelligent system for on-demand materials synthesis. This system has a real laboratory in which the synthesis of different materials requested by a remote user can be carried out. An immersive VR environment recreates the real laboratory so that a user can remotely interact with the said virtual environment so that operations can be carried out in the real laboratory.

- Work 39: *Virtual and Augmented Reality for Teaching Materials Science: A Students as Partners and as Producers Project* [69]

Bourguet et al. reported two applications based on immersive VR and AR, respectively. The first application allows a virtual Rockwell hardness test to be carried out on three different alloyed metal samples. The second application allows for checking the optical transmittance of a virtual sample of a polymethyl methacrylate, using QR codes and Epson AR glasses.

- Work 40: *Virtual Reality and Its Role in Improving Student Knowledge, Self-Efficacy, and Attitude in the Materials Testing Laboratory* [70]

Srinivasa et al. presented two applications whose purpose is to facilitate the learning of tensile tests. The first application uses immersive VR to simulate performing a tensile test in a 3D virtual laboratory. The second application uses AR coupled with Holo Lens goggles to give instructions to students as they operate a real testing machine. In addition, this paper described how to represent the contour of von Mises stress obtained by finite element analysis superimposed on the specimens of tensile and bending tests.

- Work 41: *Work-in-Progress—Teaching Invisible Phenomena and Virtual Experiments: Immersion or Augmentation?* [71]

Bourguet and Romero-Gonzalez presented five applications aimed at facilitating the understanding of certain phenomena and the performance of experiment. Two of these five applications (the one used to simulate a Rockwell hardness test and the one intended to teach about optical transmittance) were described in [69]. The three remaining applications allow the user, respectively: (i) to simulate a tensile test in a 3D virtual laboratory using immersive VR (Oculus) and Leap Motion; (ii) to visualize dislocations of materials at the atomic level in 3D using immersive VR (Google Cardboard); and (iii) to learn about fractography using AR on a mobile device by fracturing a 3D virtual sample of the material to observe the fracture process and the internal structure of the material.

3.2. Type of Published Documents

Figure 5 graphically shows how many works have been published in the form of an article, conference paper, or book chapter. As can be seen, of the 41 works selected and analyzed, 65.9% were published as conference papers, 31.7% as articles, and 2.4% as book chapters. Regarding the inclusion of empirical study in these works, 84.6% of the articles contain some type of study, and in the same way, this occurs in 48.1% of the conference papers and the only book chapter.

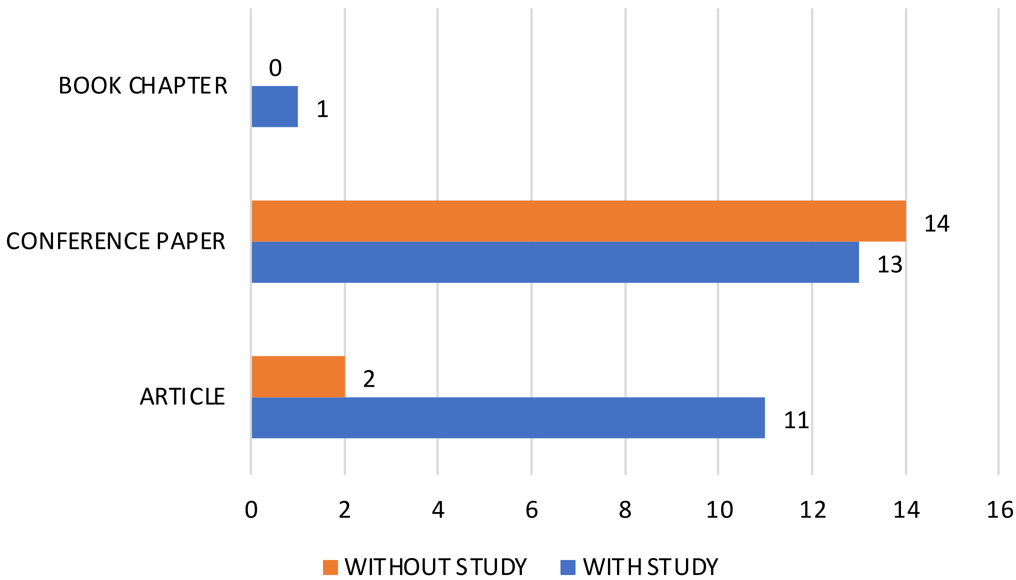

Figure 5. Type of documents analyzed, differentiating those that containing some type of empirical study from those that do not include any.

3.3. Area of MSE in Which the Applications Are Circumscribed

Each work analyzed was assigned one or more labels that identify which area or areas of MSE the application (or applications), based on RVTs, that it describes is circumscribed to. It was found that the areas of MSE into which the set of applications described fit (based on the classification widely used in the North American academic environment and by the Materials Research Society [76]) are as follows:

- Biomaterials and soft materials
- Carbon-based nanocomposite materials and applications
- Electronics, optics and quantum
- Energy and sustainability
- Material characterization
- Materials computing and data science
- Materials structure, processing, and properties

- Structural and functional materials.

In total, 49 labels were assigned to the 41 works analyzed. Figure 6 exposes these areas, indicating the number of times each of them appears in the set of works analyzed.

As can be seen, the main area for which applications based on RVTs have been developed is that of "materials structure, processing, and properties" (67.3% of the assigned labels), followed by "materials, computing and data science" (10.2%), "electronics, optics, and quantum" (8.2%), "carbon-based nanocomposite materials and applications" (4.1%), "material characterization" (4.1%), "biomaterials and soft materials" (2%), "energy and sustainability" (2%) and "structural and functional materials" (2%).

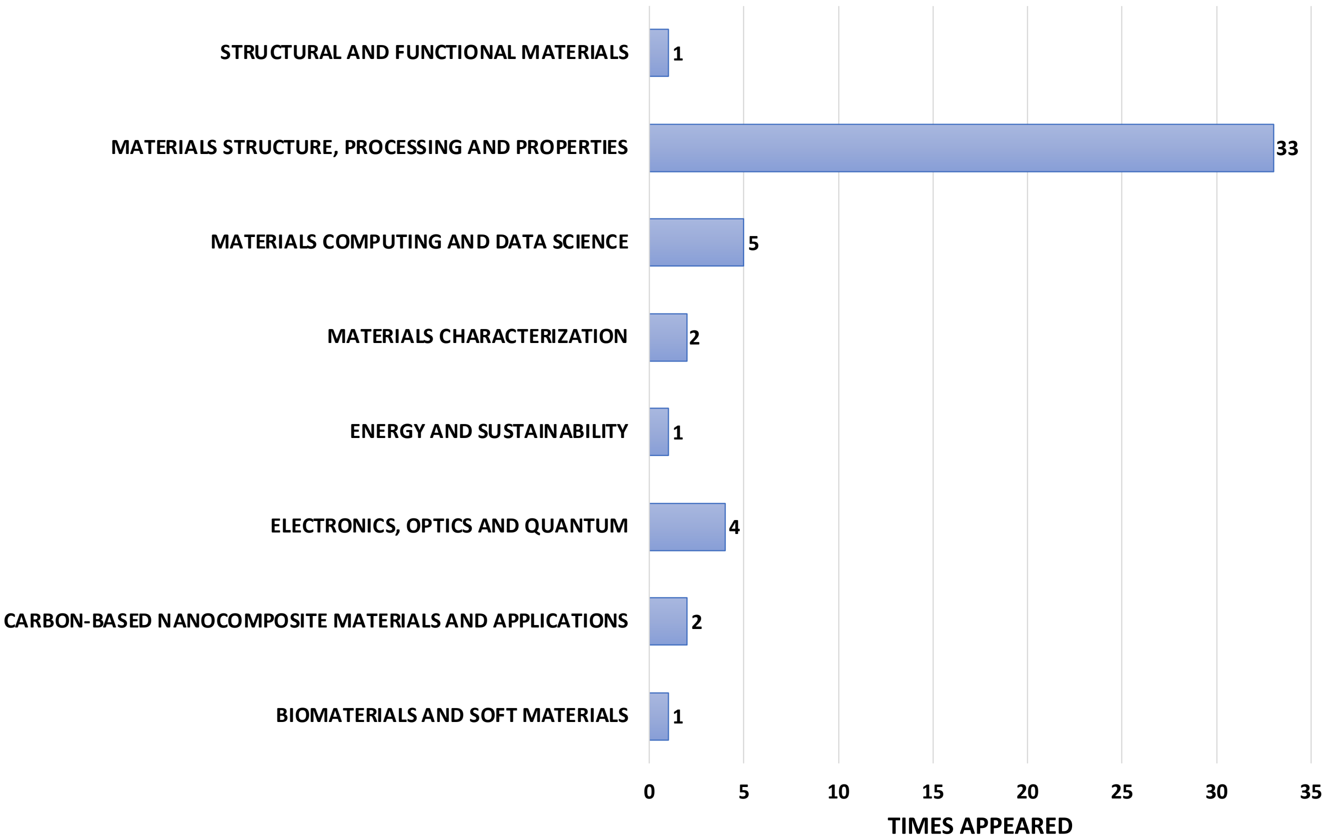

Figure 6. MSE area descriptive tags assigned to analyzed works and the number of times that these tags were used.

3.4. Purposes of the Applications

The analysis of the 41 selected papers showed that in 38 of them, their authors explicitly declared to which sectors the applications based on RVTs that they have described are directed, while in the remaining three papers, the authors did not specify this information. In this way, it was possible to determine that the sectors to which the authors of the analyzed works directed the described applications correspond to education, research, outreach and marketing. Figure 7 shows how many times applications targeting each of these sectors have been described.

As can be seen in Figure 7, on 31 occasions (58.5%), the platforms described in the papers are addressed to education, on 15 occasions (28.3%) to research, on 2 occasions (3.8%) to outreach, and on another 2 occasions (3.8%) to marketing. As indicated above, on three occasions (5.7%) no specific sector was indicated to which the applications are directed.

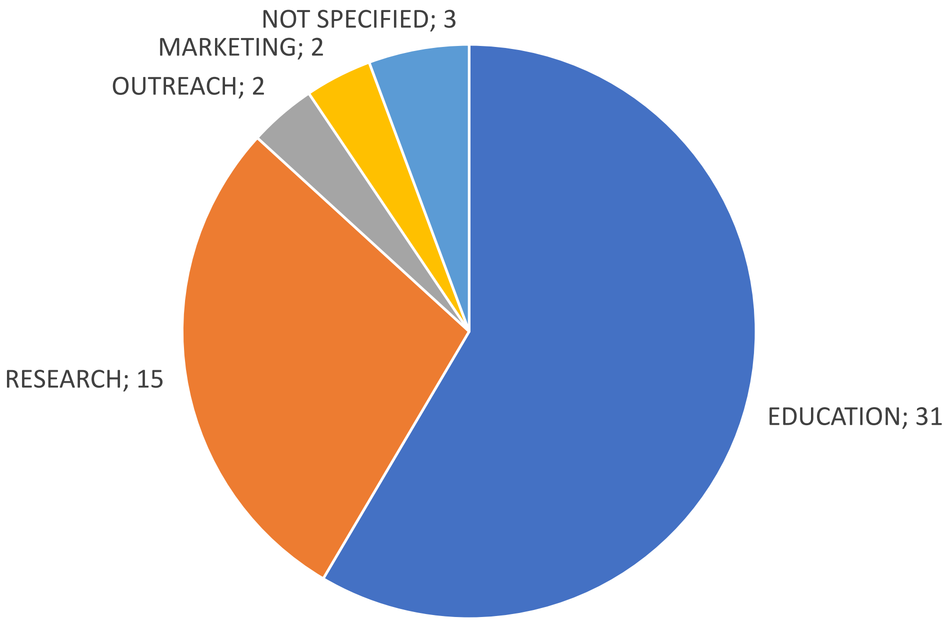

Figure 7. Number of times that the authors of the works analyzed declared directing the applications to education, research, outreach, and marketing.

3.5. RVTs Employed

From each of the works analyzed, it was extracted as to which reality-virtuality technology (or technologies) was used—that is, in each work, it was determined if it uses one or more of the following technologies: immersive VR, non-immersive VR, AR or MR. Figure 8 shows how many times each of these technologies have been used in the 41 publications analyzed.

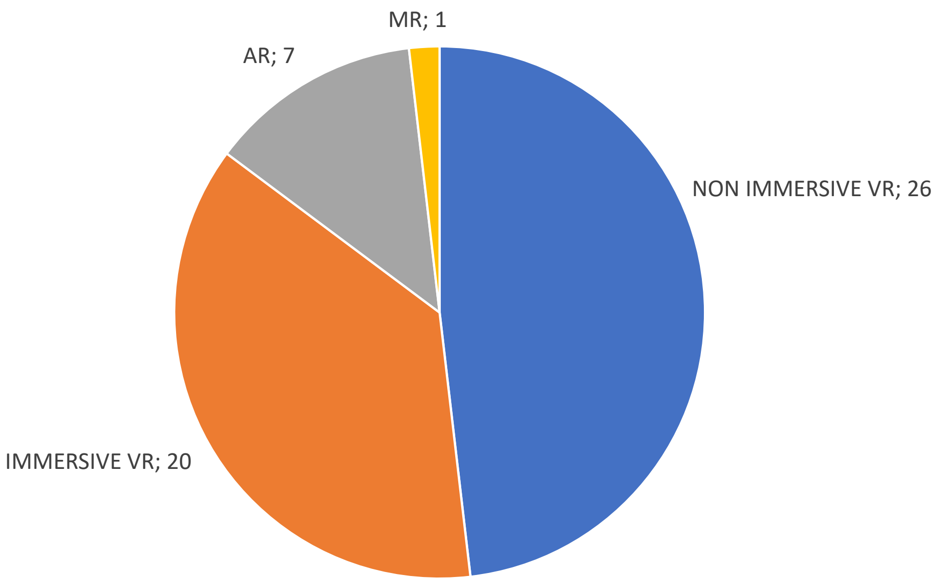

Figure 8. Number of times that immersive VR, non-immersive VR, AR, and MR technologies were used in the 41 works analyzed.

As can be seen in Figure 8, non-immersive VR was used 26 times (48.1%), immersive VR 20 times (37%), AR 7 times (13%), and MR 1 time (1.9%). On the other hand, it was determined as to which characteristics of the RVTs are exploited in each work—that is, it was determined if one or several of these characteristics are exploited: spatial vision, interactivity, and simulation. Figure 9 shows how many times these features were exploited.

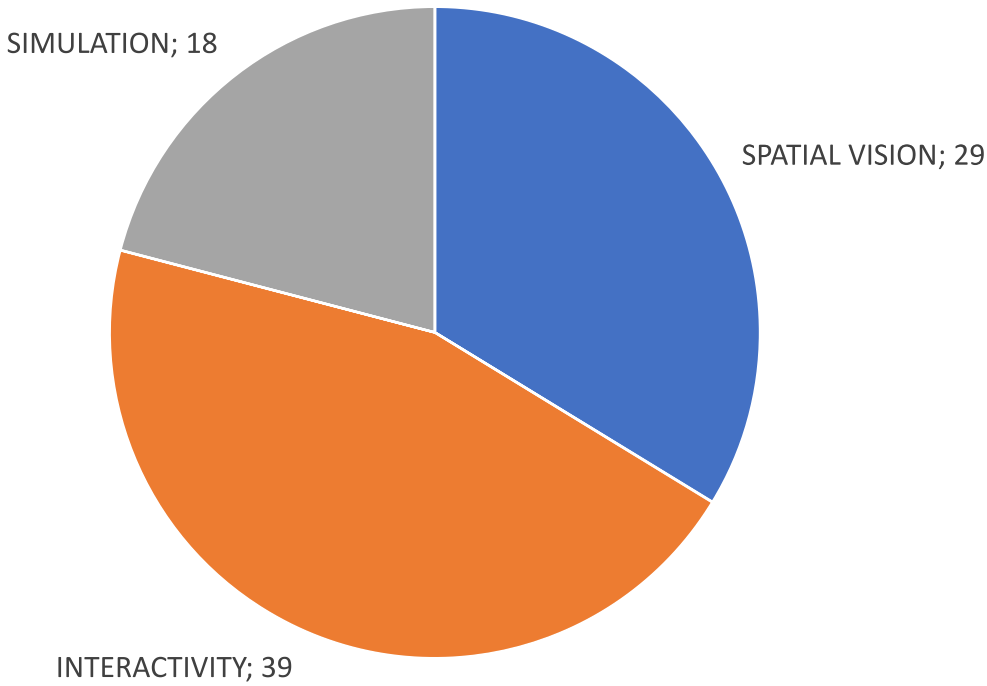

Figure 9. The number of times spatial vision, interactivity, and simulation were exploited in the works analyzed.

As can be seen in Figure 9, on 39 occasions (45.3%) interactivity options were incorporated into the described applications (Interactivity), on 29 occasions (33.7%) the ability to facilitate the user's spatial vision (Spatial Vision) was exploited, and on 18 occasions (20.9%) some type of simulator based on real devices or installations (Simulation) was described.

4. Discussion

4.1. Systematic Search

The systematic search carried out allows us to obtain a panoramic image and the state of the art [30] of the implementation of the RVTs in the field of MSE. As seen in Section "2.2.1 Search Strategy", this search was carried out on three different search platforms [30,32] using terms that explicitly link RVTs with MSE. One of the limitations of this strategy lies in the possibility that the search platforms did not show results corresponding to works in which, despite using non-immersive VR, they did not contain any reference to the expression "virtual reality". This could be the case with, for example, a job that was about "3D laboratories" or "three-dimensional resources" but made no mention of VR, AR, or MR. Another limitation of this search lies in the possibility that there are works that, despite being related to MSE, do not contain terms that coincide with those used in the search string referring to MSE and, therefore, were not shown on search platforms. This could be the case, for example, of a work in which cermets were treated but no reference was made to "materials science", "materials engineering", "materials science and engineering", "materials characterization" or "materials testing". However, after carrying out numerous tests with a greater number of terms, the authors decided not to extend the search string that was finally used, since: (i) it is practically impossible to know in how many ways the different authors of a work can refer to a non-immersive VR tool; (ii) within the MSE field, there is an infinity of areas and concepts, it being impossible to reference them all in a search equation; and (iii) an excessive number of publications would have been indexed, mostly not relevant, whose longer processing time would probably not add significant value to the present study with respect to its current forms.

4.2. Type of Published Documents

Focusing on the results obtained, most of the analyzed works are conference papers, with the number of articles being notably lower and the number of book chapters being minimal. Given that it is common for research groups to reserve the publication of their wide-ranging works for scientific journals, it is possible to hypothesize that projects involving the use of RVTs in MSE are often not among the main publications for those research groups. This could indicate that those research groups are involved in interdisciplinary projects, in which in addition to researchers directly related to MSE would be joined by others from other areas (e.g., computer science, artificial intelligence, education, etc.). This would be consistent with the fact that almost 85% of articles contain some type of empirical study that contains empirical data collection and analysis (because, as hypothesized, they would correspond to works belonging to larger projects or interdisciplinary), while this occurs in less than half of the conference papers (since, as has been hypothesized, on many occasions they would correspond to works of lesser or more narrow scope).

A limitation of this work lies in the fact that the empirical results of the works containing studies have not been analyzed. The future work that the authors consider that should be performed is to carry out an analysis of such studies. This analysis could consist of determining which aspects are evaluated in the different works and trying to analyze in an aggregate way the empirical data contained in them.

4.3. Area of MSE in Which the Applications Are Circumscribed

More than two-thirds of the works analyzed are circumscribed to the "materials structure, processing, and properties" category, being, therefore, the area of MSE in which more tools based on RVTs have been developed. This is distantly followed by categories such as "materials computing and data science" and "electronics, optics, and quantum", each of which is covered almost one in ten times. This may be because the "materials structure, processing, and properties" category includes many works that focus on materials testing and the exploration of crystallographic networks. These are fields in which the suitability of using RVTs may seem obvious, either by offering simulators to test materials [20] or by providing tools that facilitate the visualization of three-dimensional atomic structures that can be difficult to understand [23]. However, the fact that a single category includes most of the works is an indication that it is still possible to explore the feasibility of developing applications based on RVTs in other areas of MSE in which the potential benefits of this type of tools, a priori, are not as obvious as in the "materials structure, processing, and properties" area.

4.4. Purposes of the Applications

The main sector to which the analyzed platforms are directed, according to the authors of the works studied, is education, followed at a considerable distance by research, leaving outreach and marketing far behind. Considering these data, it can be assumed that the tools based on RVTs in the field of MSE are perceived as useful in the educational and research areas, but no usefulness is perceived (or there is no strong interest presently) outside of these. This could have its origin in the fact that the authors of the analyzed works are mainly university personnel—that is, personnel linked to teaching and research. Therefore, it can be concluded that there are still areas of MSE for which tools based on RVTs could be developed and their suitability investigated. To do this, it may be convenient to go to people who carry out their professional activity outside the university environment so that they can highlight problems that could be alleviated by RVTs [13]. As an example, four platforms are presented below that could be developed and investigated outside the fields of education, research, outreach, or marketing:

- Commercial scope, to show potential customers how a certain material has been created at a molecular level or what properties it has against different loads or chemical attacks.

- Industrial scope, to create visual aids that facilitate the enhancement of the work of operators involved in manufacturing processes in which there is a transformation of materials, such as the plastic part shaping industry.
- Transportation scope, to create visual and understandable tools that show shippers the estimated status of certain components that are subject to wear of fatigue and require periodic replacement.
- Construction scope, to create tools that allow comparing the real behavior of certain installed structural elements with the theoretical models used in their design.

4.5. RVTs Employed

Regarding the technology used, non-immersive VR has been used in most cases, followed closely by immersive VR, with the use of VR (immersive and non-immersive) far ahead of the rest of the technology. These results are consistent with the study performed in [23], which was focused on the learning of crystallography by means of RVTs. The use of VR is followed by AR, with the use of MR being very rare. It is notable that the use of AR currently still lags far behind the use of immersive VR. If we take into account that for several years it has been possible to run AR applications on a large number of mobile devices (smartphones and tablets) while the use of immersive VR is usually associated with the use of specific kits (e.g., a set consisting of an HMD, motion sensors, and controls) connected to computers with high 3D graphic processing capacity, one wonders what factor or factors lead researchers to opt for immersive VR and rule out AR. A possible cause may be the fact that AR usually implies that the user must hold the mobile device with one hand pointing the camera towards a specific place, which, added to the fact that the interaction with the application is carried out through the touch screen, leads to poor interactivity. In this sense, immersive VR (and non-immersive VR) allows the user to use both hands to interact with the application, either through controls, keyboard, mouse, or other devices (such as haptic gloves). This peculiarity allows the development of platforms that offer a high degree of interactivity, thus facilitating the development of tools with more functionalities and therefore greater utility.

In addition, it is possible to hypothesize that the use of MR is currently a minority due to the high price of the equipment that allows its implementation (e.g., a Microsoft Holo Lens system costs several thousand dollars). However, if this technology follows a path similar to that of others such as immersive VR, the price of this type of system will decrease over time and its use could be extended. MR is a technology that eliminates the interactivity problems that AR presents in its most widespread form of use today (in smartphones and tablets), since it leaves users' hands free and considerably expands their field of vision.

In addition, it is observed that the RVTs applied to MSE take advantage of the ability they offer to interact with virtual objects in almost half of the cases, followed by the ability to improve the user's spatial vision [23] (in almost a third of the time). The possibility of creating simulators that recreate real devices or installations [20] is the least exploited feature, being used approximately a fifth of the time. An explanation for this could be found in the fact that many researchers have found in RVTs a relatively simple way to create viewers in which complex spatial structures can be displayed, often providing them with different interaction possibilities. However, creating an application that simulates a real machine or an entire installation (such as a testing machine or entire laboratory) requires a considerably higher investment of development time [77].

4.6. Limitation and Future Direction of RVTs in the Field of MSE

The use of RVTs has experienced a significant increase in recent years in the field of engineering [15], and there are numerous examples in the particular case of MSE. One of the main limitations of the published works to date lies in the fact that most of them are focused on "materials structure, processing, and properties", leaving the rest of the MSE areas with a significant lack of research. This way, authors of future work in this area may consider focusing on other areas of MSE that have scarcely been addressed.

As seen above, larger studies and the development of complex tools based on RVTs often require the participation of multidisciplinary research groups. On the other hand, the creation of complex tools based on RVTs requires costs for implementation, time, space, development, maintenance and updating [77,78]. The necessary concurrence of these two factors is not always possible, which is a major limiting factor for the expansion of these technologies in the field of MSE. This limitation is especially important in the case of MR, as its implementation costs are high, and the development of applications is complex [79]. However, this situation is expected to change as the costs of MR hardware fall and development tools become simpler (as has been the case for AR and VR in the last decade).

The analysis carried out in this study reveals that there is a large absence of development of RVT-based tools specifically focused on activities outside the university. An important part of future research in the field of VRTs might consider the inclusion of professionals from outside the academic world in order to develop solutions to problems in MSE that exist outside academic centers or laboratories. In this sense, the work of Caudell and Mizell [13] provided an interesting example of the development of the AR concept focused on improving work on an assembly line.

5. Conclusions

In this work, a bibliographic review of academic publications has been carried out in which the use of reality-virtuality technologies (RVTs) in the field of materials science and engineering (MSE) from 2010 to 2021 is evaluated. This investigation has been carried out using Web of Science, Scopus, and IEEE Xplore, and yielded 269 results, of which 41 have been determined as relevant and have been analyzed in detail.

The analysis performed in this work has revealed that the presentation of tools based on virtual reality (VR), augmented reality (AR), or mixed reality (MR) in the field of MSE is usually found mostly in scientific conferences (65.9%). In addition, the area of MSE in which most of the analyzed works have been reported is "materials structure, processing, and properties" (67.3%), which highlights that it is possible to open new lines of research about the use of RVTs in other areas of MSE. In addition, most of the analyzed works are oriented to the educational (58.5%) and research (28.3%) sectors, which may have its origin in the fact that the authors of the publications belong to universities. In this sense, it is possible to point out the possible suitability of resorting to people related to MSE who develop their professional activity outside the university. The ideas provided by these professionals would reveal challenges and opportunities that could relate to the use of RVTs, thus opening new lines of application in sectors other than education or research.

The analysis of the technologies used reveals that VR, both in its immersive and non-immersive variants, is the most used technology (37% and 48.1%, respectively), far ahead of AR (13%). This may have its origin in the fact that AR is currently used mainly in mobile devices that, by their very nature, do not allow the creation of interactivity systems comparable to those that can be developed using VR. In this sense, even though the use of MR is still scarce (1.9%), it is expected that as this technology falls in price, its use will be extended, and it will allow alleviating the interactivity problems that AR currently presents. Furthermore, it is evident that there is still a lot of research that can be conducted focused on the use of AR and MR. Finally, it should be noted that the most exploited characteristics of RVTs are the possibility that they offer to create interactive systems (45.3%) followed by the ability of these technologies to facilitate the spatial vision of three-dimensional shapes and arrangements (33.7%) that can be complex to understand, and lastly the possibility of creating simulators (20.9%). This may be because researchers find it relatively easy to create tools based on RVTs with interactivity aimed at displaying complex three-dimensional objects, unlike what happens with simulators, whose development requires a much greater investment of time.

RVTs (VR, AR, and MR) are technologies whose use in engineering increases year after year. In this context, this paper offers a global picture of the current state of the use of RVTs in the field of MSE. Here, an interested researcher can find numerous examples of the use of these technologies in MSE and other relevant information that can help him/her open new lines of research and acquire ideas that can inspire his/her current and future work.

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Nomenclature

AR	Augmented Reality
HMD	Head-Mounted Display
IVR (used in Table 4 only)	Immersive Virtual Reality
MR	Mixed Reality
MSE	Materials Science and Engineering
NIVR (used in Table 4 only)	Non-Immersive Virtual Reality
RVT	Reality-Virtuality Technology
VR	Virtual Reality

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10. Entornos de Realidad Virtual y Aumentada para Aprender los Fundamentos de la Cristalografía

El proceso de enseñanza-aprendizaje de los conceptos relacionados con las redes cristalográficas se caracteriza por el hecho de que muchos estudiantes se enfrentan con dificultades de visualización espacial al tener que recrear mentalmente distribuciones espaciales complejas. En efecto, tanto la distribución espacial de los átomos que componen las celdas unidad como las estructuras que se forman al unir varias celdas pueden resultar conceptos difíciles de comprender cuando se utilizan métodos de enseñanza basados únicamente en representaciones gráficas bidimensionales como ocurre, por ejemplo, en los dibujos de los libros de texto impresos. Con el fin de paliar este problema, tradicionalmente se han utilizado modelos fabricados en plástico o madera que replican la forma de las estructuras cristalográficas, los cuales han sido progresivamente reemplazados por aplicaciones basadas en VR y AR.

Con el fin de conocer qué herramientas educativas basadas en VR y AR se han creado hasta el momento en el ámbito académico para dar soporte a la enseñanza de cristalografía, en la primera parte de este trabajo se ha llevado a cabo una revisión sistemática de literatura científica en que se aborda el uso de estas tecnologías para dar soporte a la enseñanza de conceptos relacionados con la cristalografía. Tras llevar a cabo una búsqueda sistemática que ha permitido seleccionar 13 trabajos relevantes, se ha hecho una breve exposición del funcionamiento de las aplicaciones descritas en cada uno de ellos, y se ha analizado una serie de parámetros relevantes concernientes a las mismas.

La segunda parte de este trabajo ha consistido en exponer el desarrollo y proceso de implementación en el aula de un VRLE basado en NIVR que persigue facilitar la enseñanza de las redes de Bravais. Esta herramienta educativa se ejecuta en un ordenador y la interacción entre el usuario y la aplicación se realiza mediante teclado y ratón. La apariencia y el manejo de este VRLE son similares a los de un videojuego en primera persona, en el cual el usuario puede explorar libremente las instalaciones de un museo. Cuando el usuario accede a la sala de exposiciones se encuentra con 14 estands, cada uno de los cuales muestra una de las redes de Bravais. Al acercarse a cada estand, el usuario puede obtener datos específicos sobre la red cristalina que contiene (por ejemplo, el factor de empaquetamiento atómico, el número de coordinación o el número de átomos por celda unitaria), así como elegir entre diferentes opciones de visualización. La primera etapa del desarrollo de este VRLE ha consistido en definir los parámetros de diseño del VRLE, tales como los conceptos que se persigue enseñar o el hardware necesario para ejecutar la aplicación, entre otros. La segunda fase de desarrollo ha consistido en modelar tridimensionalmente el entorno virtual y todos sus elementos asociados, así como aplicar materiales, texturas e iluminación. La tercera fase del desarrollo ha consistido en dotar al entorno virtual y a los elementos en él contenidos de la interactividad necesaria programando, entre otras cosas, cómo se mueve el usuario por el escenario, los botones que aparecen en pantalla, las acciones que se pueden realizar sobre las redes cristalográficas, etc. La implementación en el aula se inicia mediante clases magistrales impartidas por el profesor en las que explica los fundamentos teóricos concernientes a las redes de Bravais. Tras estas clases, los estudiantes utilizan individualmente el VRLE en el aula bajo la supervisión del profesor, teniendo la posibilidad de seguir utilizándolo sin supervisión fuera del horario lectivo todo el tiempo que deseen. Posteriormente, los estudiantes forman grupos para resolver un ejercicio y, por último, responden encuestas. Los datos extraídos de estas encuestas permiten a los investigadores obtener información de interés como por ejemplo la efectividad formativa de la aplicación, su aceptación por parte de los alumnos o aspectos técnicos que requieren ser mejorados.

crystals

MDPI

Article

Virtual and Augmented Reality Environments to Learn the Fundamentals of Crystallography

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Abstract: Nowadays, there are many situations in which information and communications technology (ICT) is used as a vehicle to transmit knowledge. The fast evolution of technology in recent decades has favored the development of virtual reality (VR) and augmented reality (AR) and with them the emergence of virtual laboratories (VLs) using VR or AR. Since such technologies can help students understand the atomic spatial distribution, crystallography is a discipline that has taken advantage of the use of VL in the teaching of crystal lattices, thus solving the usual educational problem of visualization in two- and three-dimensions. This paper presents a literature review that helps to identify the main features of VLs (based on VR or AR) that have been developed in the academic field to support the learning of crystallography concepts. Furthermore, this paper describes a VL developed by the authors where students can learn the main contents related to the 14 Bravais lattices (unit cells, directions, crystallographic planes, interstitial sites, etc.) by exploring the stands of a virtual museum. Such a VL uses non-immersive VR and has been designed based on the authors' long-term research to achieve a high learning effectiveness educative platform.

Keywords: crystallography; crystalline structures; Bravais lattices; materials science and engineering; virtual reality; augmented reality; virtual reality learning environments; virtual laboratory; spatial comprehension

1. Introduction

The teaching and learning process of crystal lattices is characterized by presenting difficulties of spatial visualization when having to mentally recreate complex spatial distributions [1]. Both the spatial distribution of the atoms that make up the unit cells and the structures that are formed by joining them can be concepts that are difficult for many students to understand when using teaching methods based solely on two-dimensional graphic representations (as, for example, in the drawings of traditional textbooks). To address this problem, typically, models made of polymeric materials or wood have been used to replicate the shape of crystallographic structures [2]. However, this practice has disadvantages such as high cost of commissioning the manufacture of new custom-made models [2] or the limitations of its handling (e.g., it is difficult to create sections of the unit cells to visualize planar density or linear). On the other hand, in the last decades, tools based on information and communications technology (ICT) have been developed that aim to improve the spatial understanding that students have when they approach the learning of crystallographic structures.

In this sense, crystallographic structure repositories are known, such as those that are stored in databases such as the Crystallography Open Database (COD) [3] or the one that is hosted in the Cambridge Crystallographic Data Center (CCDC) [4]. This data can be downloaded for later processing in programs such as VESTA [5] or Mercury [6,7], which offer a multitude of crystallographic analysis options, among which are different choices for viewing and exploring three-dimensional crystallographic models of crystallographic networks.

Another example of the use of ICT applied to the teaching of crystallography is found in 3D printing. Thanks to the reduction and expansion that 3D printers have experienced, there are several works [2,8–10] that describe methods to create three-dimensional impressions of customized crystallographic structures. These physical models are subsequently freely explored by the students in the same way that would be done with traditional models made of polymeric materials or wood, but offer a series of advantages with respect to the former, such as: (i) the creation of rapid and low-cost physical models given the low price that 3D printers currently have and the material used in printing, (ii) the possibility of printing structures hosted in COD or CCDC [8], (iii) the possibility of customizing the size of the elements that make up the crystallographic structures [8], and (iv) the possibility of printing complex structures [2], among others.

Conversely, the rapid evolution that ICT has undergone has favored that in recent years there has been a great development of virtual reality (VR) and augmented reality (AR) technology [11,12]. Indeed, although VR was conceptually defined in 1965 by Ivan Sutherland [13] as the way to make the virtual world shown on the screen look, sound, and feel real, it was not until well into the last decade that hardware has allowed the improvement and cheaper and consequent expansion of VR and AR in the educational sectors. These technologies allow the creation of didactic tools with high efficiency at the formative level, improving the teaching-learning process in university training [14–22]. Some of the cases in which the use of this technology is especially useful are in those where it is required to improve students' spatial understanding to help them comprehend concepts related to complex spatial structures [1,23–27], as is the case with learning crystallographic structures.

There are currently various computer applications that use VR (both immersive and non-immersive) and AR to support the teaching of different aspects related to crystallography. By way of clarification, immersive VR (IVR) is one that immerses the user in the virtual environment, normally through a VR glasses system known as a head-mounted display (HMD), while non-immersive VR (NIVR) is one that usually shows the virtual environment on flat screens of standard devices such as computers or smartphones [28,29]. To know the state of the art, that is, what ICT tools based on VR and AR have been created in the academic field so far to support the teaching of crystallography, the authors of this article have carried out a systematic search in two multidisciplinary databases: (i) Web of Science (WOS) and (ii) Scopus. This article presents the exact methodology that has been followed to perform the systematic search, in addition to describing each of the relevant results that this search has yielded.

Virtual reality learning environments (VRLEs) are applications that are based on the use of VR to create virtual learning environments and both their development and use in university classrooms have been studied in different works [15,19–22,30–33]. Different works by Vergara et al. [29,34–37] describe the process that must be followed to create and use a VRLE, addressing the process that includes the initial considerations, design, development, use in the classroom, evaluation, and improvement. The methodology described in these studies allows the creation of VRLEs that facilitate students to achieve a high level of meaningful learning (i.e., that the knowledge taught is fully understood by the student and is able to relate it to other previously learned concepts [34]), in addition to ensuring that the effectiveness at the formative level of these tools does not decrease over the years due to technological obsolescence [35]. Based on what is described in these studies, the authors have developed a VRLE that aims to serve as a tool for engineering students who approach learning the 14 Bravais networks. This article describes the design and development parameters that have been incorporated into this VRLE, which allow to infer that it will be an effective tool in teaching basic concepts of crystallography.

2. Systematic Literature Review

The systematic search carried out by the authors seeks to know what tools based on VR and AR have been developed so far in the academic field to support the teaching of concepts related to crystallography. For this, two search equations have been designed, one to be run on the WOS platform and the other for the Scopus database. The fact that a different search equation has been created for each system is because each one uses different terminology and search terms (e.g., in WOS the expression "crystal" returns results that contain the exact term "crystal", while in Scopus this same expression returns both the term "crystal" and its plural form "crystals").

The search equations have been designed to index those works related to the teaching of crystallography and that make use of VR or AR. For this, the search for terms has been carried out in the fields of title, abstract and keywords, in such way that the following terms are contained in one or more of the mentioned fields: (i) "crystal" (or any of its variants, such as crystallography, microcrystalline, etc.) or "nanostructure" (or its plural, "nanostructures"), (ii) terms related to teaching (all variants of teaching, learning, training or education), and (iii) terms related to VR or AR technology (the exact expressions virtual reality, augmented reality, the variants of virtual laboratory, the singular/plural of virtual environment or the concept of didactic virtual tool). Table 1 lists the expressions used in the search equations and examples of terms that databases return.

Table 1. Expressions used in the search string and examples of words returned by databases.

Expression Used in the Search String	Examples of Words Returned by Databases
crystal	crystallography, crystalline, microcrystalline
nanostructure$ [1]	nanostructure, nanostructures
teach*	tech, teaching
learn*	learn, learning
train*	train, training
educati*	education, educative
"virtual reality"	virtual reality
"augmented reality"	augmented reality
"virtual lab*"	virtual lab, virtual labs, virtual laboratory
"virtual environment$"[1]	virtual environment, virtual environments
"didactic virtual tool$"[1]	didactic virtual tool, didactic virtual tools

[1] $ symbol to be used in WOS only.

The literature search has not been temporarily bounded in either WOS or Scopus and, therefore, publications have been indexed from the present to the oldest included in each database. Each search process has been refined to allow for the indexing of all types of publication (articles, proceedings, book chapters, etc.) and to exclude those papers that are written in a language other than English. The date of the searches described in the following sections (both in WOS and Scopus) is 1 May 2020.

2.1. Search Results in WOS

The search on the WOS platform has been carried out in its core collection database, including all its indexes. Since the advanced search in WOS allows to search simultaneously in the title, abstract and keywords using only the field "topic" – which is identified with the field tag TS-, the search criteria used was the following:

TS = ((*crystal* OR nanostructure$) AND (teach* OR learn* OR train* OR educati*) AND ("virtual reality" OR "augmented reality" OR "virtual lab*" OR "virtual environment$" OR "didactic virtual tool$"))

The results obtained using this search equation have been refined as previously described (i.e., without temporal dimensioning, allowing to index all types of publications and excluding those that are not written in English). In this way, 43 search results have been obtained, the oldest of which was from 1997 [38].

2.2. Search Results in Scopus

Scopus itself constitutes a single database and, therefore, it is not necessary to select a specific database in which to perform the search, which has been carried out using the fields "title", "abstract" and "author keywords". Thus, the search criteria used were as follows:

TITLE((*crystal* OR nanostructure) AND (teach* OR learn* OR train* OR educati*) AND ("virtual reality" OR "augmented reality" OR "virtual lab*" OR "virtual environment" OR "didactic virtual tool")) OR ABS((*crystal* OR nanostructure) AND (teach* OR learn* OR train* OR educati*) AND ("virtual reality" OR "augmented reality" OR "virtual lab*" OR "virtual environment" OR "didactic virtual tool")) OR AUTHKEY((*crystal* OR nanostructure) AND (teach* OR learn* OR train* OR educati*) AND ("virtual reality" OR "augmented reality" OR "virtual lab*" OR "virtual environment" OR "didactic virtual tool"))

As in the case of WOS, the results obtained using this search equation have been refined as previously described (i.e., without temporal dimensioning, allowing to index all types of publications and excluding those that are not written in English). In this case, 59 results have been obtained, of which the oldest paper was published in 1995 [39].

2.3. Analysis of Indexed Results (WOS and Scopus)

As noted in the previous sections, WOS has returned 43 results and Scopus 59, with 23 of them being duplicate results (they are indexed in both the WOS and Scopus searches). After eliminating the duplicate results, the total number of unique results indexed between the two systems is 79. Of these 79 unique results, after analyzing the content of the abstract of each one, only those works that describe platforms based on VR or AR and that are focused on understanding concepts related to crystallographic structures are selected. Thus, a total of 13 relevant works has been identified, all of them in a paper, proceeding or book chapter format. The process followed to carry out the search and select the relevant works is summarized in the schematic shown in Figure 1.

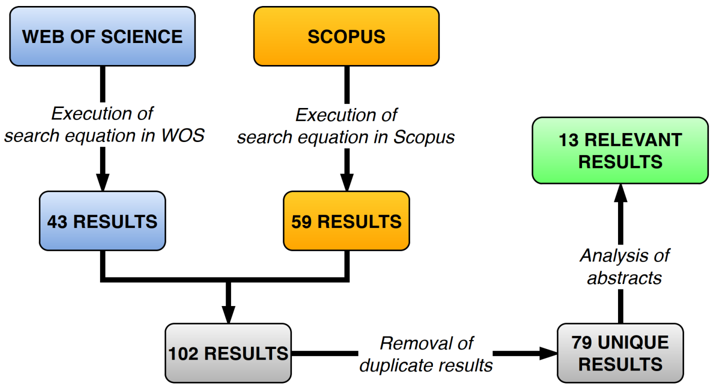

Figure 1. Summary of the literature review process followed to select the relevant research works in the instruction of fundamentals of crystallography by virtual learning environments.

The titles of the 13 selected works are listed below, along with the year of their publication:

- Recent developments in virtual reality-based education, 1996 [40].
- Collaborative augmented reality for inorganic chemistry education, 2008 [41].
- Learning about the unit cell and crystal lattice with computerized simulations and games: A pilot study, 2010 [42].
- New augmented reality applications: Inorganic chemistry education, 2011 [43].
- Development of an educational virtual transmission electron microscope laboratory, 2014 [44].
- An immersive 3D virtual learning environment for analyzing the atomic structure of MEMS-relevant materials, 2015 [45].

- Beyond the flipped classroom: A highly interactive cloud-classroom (HIC) embedded into basic materials science courses, 2016 [46].
- A virtual resource for enhancing the spatial comprehension of crystal lattices, 2018 [47].
- Can virtual reality enhance learning: A case study in materials science, 2018 [48].
- NOMAD VR: Multiplatform virtual reality viewer for chemistry simulations, 2018 [49].
- A virtual laboratory for learning fullerene production and nanostructure analysis, 2018 [50].
- Application of virtual reality for learning the material properties of shape memory alloys, 2019 [51].
- Visualizing 3D molecular structures using an augmented reality app, 2020 [52].

The virtual platforms described in each of the previous works are described individually in the following section, except for [41] (published in 2008) and [43] (published in 2011), since both have been written by the same author, have been developed at the same university and describe the same type of platform. In particular, the work described in [43] can be interpreted as a more detailed extension of the work described in [41], and for this reason, only the platform exposed in [43] is described.

Figure 2 shows thumbnails of images extracted from each work [40–52] to offer the reader a clearer idea of the look of the platforms described. In addition, Figure 2 classifies the described platforms according to the technology used by each of them: NIVR [40,42,44,47], IVR [45,48,49], IVR and NIVR [50,51], and AR [41,43,46,52].

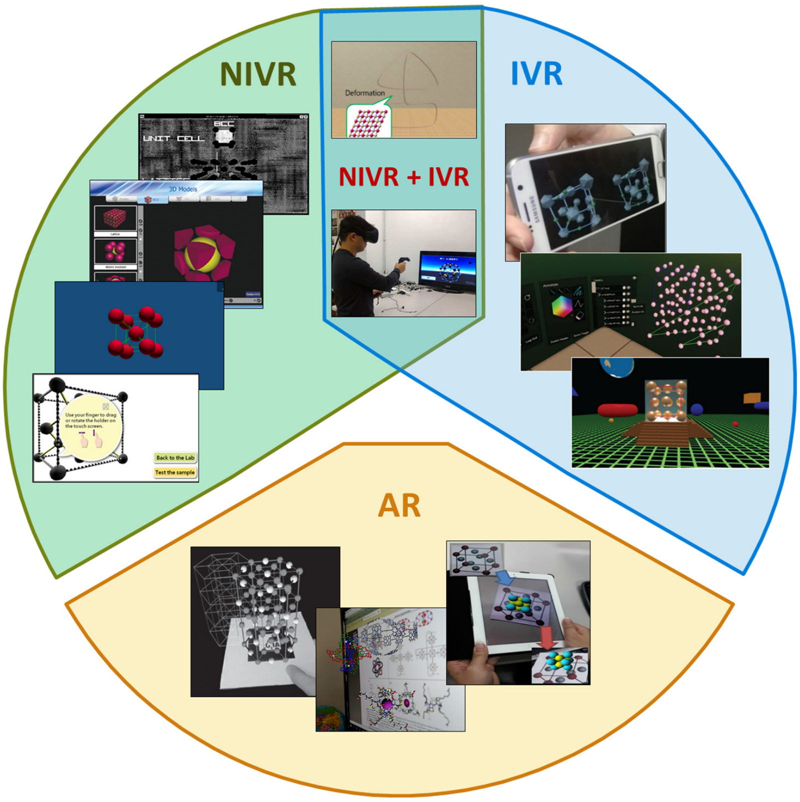

Figure 2. Thumbnails of the described platforms and their classification according to the used technology (NIVR, IVR or AR).

3. Description of the Relevant Works

This section presents a summary description of the virtual crystallographic network platforms presented in each of the thirteen research works [40–52] selected through the systematic search. Each description has been made in such a way that it includes the following data (as long as they are available in their corresponding work): (i) year of the first publication of the work in which the platform is presented; (ii) concepts it aims to teach and its relation to crystallography; (iii) type of technology used, that is, NIVR, IVR, or AR; (iv) hardware used to use the application; (v) description and object of the study carried out on the task; and (vi) other data. Table 2 summarizes these aspects for each of the research works considered. Note that, in Table 2, the column labeled "year" refers to the year of the first publication of the work. For sake of clarity, the following terminology has been used from now on: BCC (body-centered cubic), FCC (face-centered cubic), HCP (hexagonal close-packed), DC (diamond cubic), TEM (transmission electron microscope), MEMS (micro-electro-mechanical systems), SMA (shape memory alloy), PC (personal computer), and CAVE (cave automatic virtual environment).

Table 2. Summary of the main features of each platform studied.

Article	Year	Main Crystallographic Concepts Taught	Technology	Hardware	Study Included
[40]	1996	• BCC cells • Lattices	NIVR	• PC	No
[42]	2010	• Primitive cubic cells • BCC cells • FCC cells • HCP cells • Lattices	NIVR	• PC	Yes
[43]	2011	• BCC cells • FCC cells • HCP cells • Tetrahedral structures • Bravais lattices • Crystallographic planes	AR	• PC • Markers	Yes
[44]	2014	• Use of TEM • Crystal structure and diffraction patterns of diamond, graphite and TiO_2	NIVR	• Smartphone • Tablet	Yes
[45]	2015	• Atomic structure of monocrystalline materials relevant to MEMS	IVR	• PC & HMD • Controller	No
[46]	2016	• Primitive cubic cells • BCC cells • FCC cells • HCP cells	AR	• Smartphone • Tablet • Markers	Yes
[47]	2018	• Primitive cubic cells • BCC cells • FCC cells • Bravais lattices	NIVR	• PC	Yes
[48]	2018	• BCC cells • FCC cells • DC cells • HCP cells	IVR	• PC & HMD • Controller	Yes
[49]	2018	• Any type of unit cell • Lattices • Complex structures • Evolution of chemical reactions	IVR	• PC & HMD • CAVE • Smartphone • Controller	Yes
[50]	2018	• Use of TEM • Structure and diffraction patterns of fullerenes	IVR / NIVR	• PC & HMD • Controller • Smartphone • Tablet	Yes
[51]	2019	• SMA atomic structure modification	IVR / NIVR	• PC & HMD • Controller • Smartphone • Tablet	Yes
[52]	2020	• Any type of atomic structure	AR	• Smartphone • Tablet	No

3.1. Reference [40]: Recent Developments in Virtual Reality Based Education

This work was published in 1996 and it presents an application divided into modules, each module is dedicated to teaching a concept related to chemistry. In one of these modules, the arrangement of the atoms in a unit cell of the BCC type is taught, as well as the crystalline structure that forms the union of several unit cells of this type. The type of technology used by this application is NIVR and runs on a PC. As indicated in the work, at the time of publication this module had not yet been evaluated with students and therefore does not include the corresponding analysis.

3.2. Reference [42]: Learning about the Unit Cell and Crystal Lattice with Computerized Simulations and Games: A Pilot Study

This work was published for the first time in 2010 and it presents two modules oriented to the teaching of cubic primitive unit cells (BCC, FCC, and HCP) as well as the crystalline structure that forms the union of several unit cells of these structure types. The type of technology used by this application is NIVR and runs on a PC. This investigation includes a study in which 23 science students used the application and answered questionnaires whose responses were subsequently analyzed by the authors of the work. The purpose of this study was to determine the effectiveness of the application by improving the learning of the unit cells and crystallographic networks, in addition to evaluating the opinion of students after using the application.

This application is divided into two main modules. The first module allows: (i) freely exploring the unit cells and the networks they form; (ii) learn a method to deduce the unit cell from a crystal lattice; (iii) visualize how a crystal lattice is generated by moving the unit cell along the three main orthogonal planes. The second module of the application consists of a game in which the user must collect atomic pieces that belong to a unit cell to later place these pieces in the place of the corresponding unit cell. This type of platform with two modules, one that develops the theoretical part using VR and the other with educational exercises, is quite common [14,53].

3.3. Reference [43]: New Augmented Reality Applications: Inorganic Chemistry Education

This work was first published in 2011 and constitutes a continuation of the platform presented in a previous work of the same authors in 2008 [41]. The objective of this platform is to teach concepts related to unit cell of type BCC, FCC, HCP as well as Bravais lattices, tetrahedral structures, crystallographic planes or sets of unit cells. The type of technology used by this application is AR, running on a PC to which several cameras are connected to capture images of the real environment and detect certain markers. Each of these markers has a certain virtual element associated (e.g., a certain unit cell). The images captured by the cameras are superimposed with the virtual elements associated with each marker and displayed on a screen by using a projector. This platform allows the user to move and rotate the markers to change the point of view of the virtual elements displayed through the projector. The objective of this study was to find out the opinion of the students about the educational platform. In this investigation, 15 students from the University Jaume I (Spain) participated in course subjects ranging from Materials Sciences, Ceramic Inorganic Chemistry, and Advanced Chemistry Laboratory. After using the application, the students filled out surveys whose results were later analyzed by the authors of the work. The conclusions of the study indicate a high acceptance of this platform by the students.

3.4. Reference [44]: Development of an Educational Virtual Transmission Electron Microscope Laboratory

This work was published for the first time in 2014 and it presents a platform that aims to teach how to use a TEM, on the one hand, and the crystal structure of three materials and their respective diffraction patterns, on the other hand. The type of technology used by this application is NIVR and runs on a smartphone or tablet, carrying out the interaction between the user and the application through the touch screen of the given device. This study aimed to evaluate the effectiveness of the application in teaching nanostructural analysis. Thirty-eight students from the Department of Applied Science at the University of Hsinchu (Taiwan) and 36 other students (mostly high school students) participated in the study, who used the application or viewed instructional videos, before and after which they filled in questionnaires whose answers were later analyzed by the authors of the work. The study concluded the learning achievement of the students who used the platform was superior to that obtained by the students who viewed videos. Also, the students who used the platform rated it positively.

This application recreates a virtual TEM that the user can learn to operate using information that the application itself offers. The crystalline structures of three materials (diamond, graphite, and titanium oxide) are presented, which the user can rotate to become familiar with the spatial arrangement of the atoms that make up their structures. After exploring the crystalline structures, the user can carry out the observation in the microscope of each one of the material samples and observe the diffraction pattern obtained for each one of them. Finally, the user can perform an online test to assess the level of knowledge acquired.

3.5. Reference [45]: An immersive 3D Virtual Learning Environment for Analyzing the Atomic Structure of MEMS-Relevant Materials

This work was published in 2015 and it presents a platform that aims to teach concepts related to the atomic structure of monocrystalline materials used in MEMS (e.g., silicon, chromium, titanium, and copper). The type of technology used by this application is IVR, visualizing the virtual environment using an HMD connected to a PC and carrying out the interaction between the user and the virtual environment using a game controller. This study did not include any statistical study with students.

This application allows access to a laboratory in which the user can select and read relevant information about a material. Subsequently, the user can interact in real-time with the atomic structure of the previously selected material, analyzing key parameters of the crystal lattice such as the number of atoms in the lattice, atomic packing factor, linear atomic density, etc.

3.6. Reference [46]: Beyond the Flipped Classroom: A Highly Interactive Cloud-Classroom (HIC) Embedded into Basic Materials Science Courses

This work was published for the first time in 2016 and it presents a platform that aims to teach materials science concepts. This platform contains two modules, one of them focused on the teaching of the cubic primitive type unit cells (BCC, FCC and HCP). The type of technology used by this application is AR and runs on a smartphone or tablet, carrying out the interaction between the user and the application through the touch screen of these devices, requiring the use of the integrated photo camera on the device.

This work evaluates the educational effectiveness of using the AR platform in a Materials Science course, comparing it with traditional teaching methodology. In this study, 92 second-year students from the University of Science and Technology (Taoyuan County, Taiwan) participated. They were divided into two groups that received the same materials science course but in two different modalities: through the platform (experimental group) and following the traditional teaching methodology (control group). Both before and after receiving the course in either of the two modalities, the students answered questionnaires whose answers were later evaluated by the authors of this work. The study concluded that students who used the AR platform had better results across three analyzed learning dimensions (knowledge, comprehension and application in a basic materials course) compared to those students who had not used it.

This application allows the user to focus on the camera of a smart device (smartphone or tablet) on a certain image of a unit cell (instead of a market such as those commonly used in AR-based applications) so that an image appears on its 3D cell unit under study. The user can then, by using the touchscreen, rotate the unit cell to see it from different angles, view interactive animations and videos, etc.

3.7. Reference [47]: A Virtual Resource for Enhancing the Spatial Comprehension of Crystal Lattices

This work was first published in 2018 and it presents a platform that aims to make it easier for students to understand the position of atoms within crystal lattices. The type of technology used by this application is NIVR and runs on a PC. This study aimed to know the opinion that students have about various aspects of the platform. Forty Mechanical Engineering Degree students at the Catholic University of Ávila (Ávila, Spain) received master's level courses on Bravais networks, used the platform, and solved exercises, after which each student answered questions via a survey. The study concluded that students rated positive aspects of the use, design, and teaching effectiveness of the platform.

This application allows the user to choose one of the 14 Bravais networks (which are grouped into seven crystalline systems) to carry out on each one them different operations such as rotating and obtaining views of sections or their expanded set.

3.8. Reference [48]: Can Virtual Reality Enhance Learning: A Case Study in Materials Science

This work was first published in 2018 and it describes a method of using the Arthea Visualizer [54] to teach concepts related to BCC, FCC, DC, and HCP type of unit cells. The type of technology used by this application is IVR, visualizing the virtual environment using an HMD connected to a PC and carrying out the interaction between the user and the virtual environment using a controller. The objective of this study was to evaluate the usability and effectiveness of the teaching method described in it (based on the use of Arthea). Students from STEM (science, technology, engineering, and mathematics), six of them undergraduate and one graduate, at the University of Michigan (USA) participated in this study. During the investigation, a group of students carried out a series of activities using Arthea while another group of students carried out the same activities using paper and pen. After completing the activities, the students answered a questionnaire whose results were analyzed by the authors. Although the number of participating students in this study was very small, the authors noted that issues related to spatial reasoning were best resolved by those who had used Arthea.

The teaching method revealed in this work consists of creating 3D models of unit cells and crystalline networks to later visualize them on an HMD using the Arthea application. Arthea allows visualizing 3D models in different HMD systems, as well as making drawings on them [48,54].

3.9. Reference [49]: NOMAD VR: Multiplatform Virtual Reality Viewer for Chemistry Simulations

This work was published for the first time in 2018 and it presents a platform that aims to visualize both atomic structures and chemical reactions at the atomic level. The type of technology used by this application is IVR, allowing the virtual environment to be viewed using different types of hardware: HMD connected to a PC, HMD with a smartphone attached in front of the user's eyes, and CAVE system. To facilitate the reader's understanding, the CAVE system projects images on all the surrounding walls, ceiling, and floor of a room so that users, equipped with stereoscopic goggles, are immersed in a three-dimensional virtual environment [28,55]. The interaction between the user and the application is generally carried out through a controller. This study does not include any statistical study with users of the platform.

The platform described in this work is not only intended to serve as an educational tool but also has other objectives, such as serving as a tool for researchers. This platform constitutes a visualizer that can be used to visualize the result of common computer simulations of the evolution of chemical reactions and other interesting data representations used in materials science, such as unit cells and crystallographic networks. This platform allows viewing in three dimensions materials science datasets created by the user as well as datasets obtained from the repository for materials science data NOMAD [56].

3.10. Reference [50]: A Virtual Laboratory for Learning Fullerene Production and Nanostructure Analysis

This work was published for the first time in 2018 and it presents a platform that aims to teach concepts related to the fullerenes as well as familiarizing students with how a TEM works. This application can use two types of technology: (i) IVR, visualizing the virtual environment through an HMD connected to a PC, carrying out the interaction between the user and the virtual environment through a controller, and (ii) NIVR, displaying the virtual environment on a smartphone or tablet, carrying out the interaction between the user and the application through the touch screen of the device being used. This study aimed to evaluate the effectiveness of the application in teaching production and analysis of fullerenes, for which sixty-seven students from a senior high school at Hsinchu (Taiwan) participated. A control group viewed instructional videos while the experimental group used the educational platform, before and after which they filled in questionnaires whose answers were later analyzed by the authors of the work. The study concluded that the learning achievement of the students who used the platform was superior to that obtained by the students who viewed videos. Also, the students who used the platform rated it positively.

This application allows the user to produce fullerenes with an arc-discharge apparatus and use a TEM to observe their geometrical structure and diffraction pattern. Furthermore, the platform has a module that allows the user to perform the assembly of fullerene structures by moving carbon atoms to the bonding position one by one. Once the assembly of a fullerene is completed, the application allows the user to send the created model to a 3D printer to fabricate a corresponding physical model.

3.11. Reference [51]: Application of Virtual Reality for Learning the Material Properties of Shape Memory Alloys

This work was published for the first time in 2019 and it presents a platform that aims to teach concepts related to SMAs. Among the concepts taught is the variation that the crystalline structure undergoes when passing from the martensite phase to the austenite phase and vice versa when the material is subjected to successive deformation-heating-cooling processes. This application can use two types of technology: (i) IVR, visualizing the virtual environment through an HMD connected to a PC, carrying out the interaction between the user and the virtual environment through a controller, and (ii) NIVR, displaying the virtual environment on a smartphone or tablet, carrying out the interaction between the user and the application through the touch screen of the device being used. The purpose of this study was to measure the performance of this platform in learning the SMAs properties and applications. A total of 132 students from the Department of Materials Science at a university in North Taiwan participated in this study. The students were divided between a control group, which carried out a real experiment, and an experimental group, which performed the same experiment but virtually using the educational platform. Both before and after the experiment (real or virtual), the students filled out questionnaires whose results were subsequently analyzed by the authors of this work. The study concluded that the learning effectiveness of the platform was higher than performing the real experiment. Moreover, the students reported positive feedback to the use of the platform.

This platform allows the user to interactively learn concepts related to SMAs, such as their crystalline structure or practical applications. Among other options, this platform allows one to carry out virtually a process by which a wire of a SMA is successively deformed, heated, and cooled to show (in a simplified way) the different configurations that its crystalline structure adopts.

3.12. Reference [52]: Visualizing 3D Molecular Structures Using an Augmented Reality APP

This work was first published in 2020 and it presents a methodology to create an application that allows the user to visualize in 3D any molecular structure based on crystallographic data or from computer modeling. This work describes a platform developed according to this methodology and which serves to visualize complex structures (i.e., the porphyrin nanoball). The type of technology used by this application is AR and it runs on a smartphone or tablet, requiring the use of the integrated photo camera on the device. This paper does not include a study of the described platform, but it is noted that 24 students from a high school in Denmark used it successfully.

The applications created following the methodology described in this work allow the user to focus on the camera of a smart device (smartphone or tablet) on a certain image of an atomic structure (instead of a market such as those commonly used in AR-based applications). In this way, the three-dimensional atomic structure superimposed on the real environment appears on the smart device's screen, making it possible to move the device to view it from different angles.

4. VRLE for Teaching Bravais Lattices

A VRLE developed by the authors is presented in this section. This VRLE, which serves to support the university education of the 14 Bravais networks, is presented as a NIVR-based application that runs on a PC, with the interaction between the user and the application being carried out using a keyboard and a mouse. The appearance and handling of this VRLE are similar to that of a first-person shooter video game, in which the user can freely explore the facilities of a museum (i.e., exhibition hall, office, bathroom and classroom), most of them are shown on Figure 3. When the user accesses the museum's exhibition hall, she or he finds 14 stands (Figure 3b), each of which shows one of the Bravais networks. By approaching each stand, the user can obtain specific data on the crystal lattice it contains (e.g., atomic packing factor, coordination number, or the number of atoms per unit cell) as well as to choose between different display options, whose aim is to reinforce the spatial comprehension of the crystal lattice (Figure 4): (i) full rotation and translation of the lattice; (ii) different views of the lattice (the unit cell only, the expanded lattice, etc. Figure 4b–e); (iii) tetrahedral and octahedral interstitial voids (in both the unit cell and the expanded lattice); (iv) crystallographic directions and planes, indicating the corresponding Miller indices (in both the unit cell and the expanded cell); (v) families of both crystallographic directions and planes; and (vi) gathering of specific sections or subsets of data. This VRLE was designed with a high level of interactivity, thus favoring the user a better spatial comprehension of the concept of crystal lattices. A complementary video is available in the Supplementary Material of this paper so that the reader can better visualize all the options shown in Figure 4.

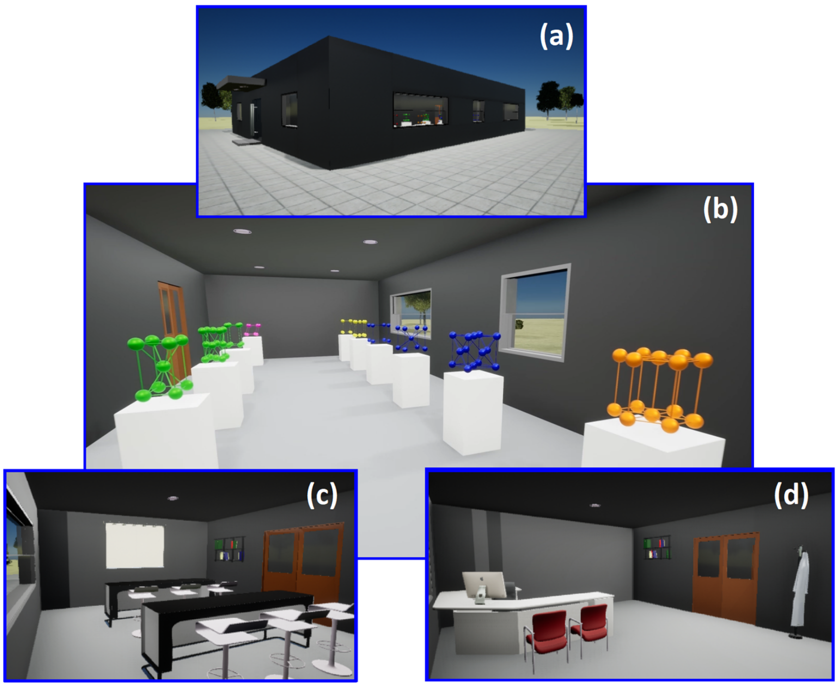

Figure 3. Screenshots of the museum facilities that users can freely explore: (**a**) exterior view of the building; (**b**) crystal lattices exhibition hall; (**c**) classroom; and (**d**) office.

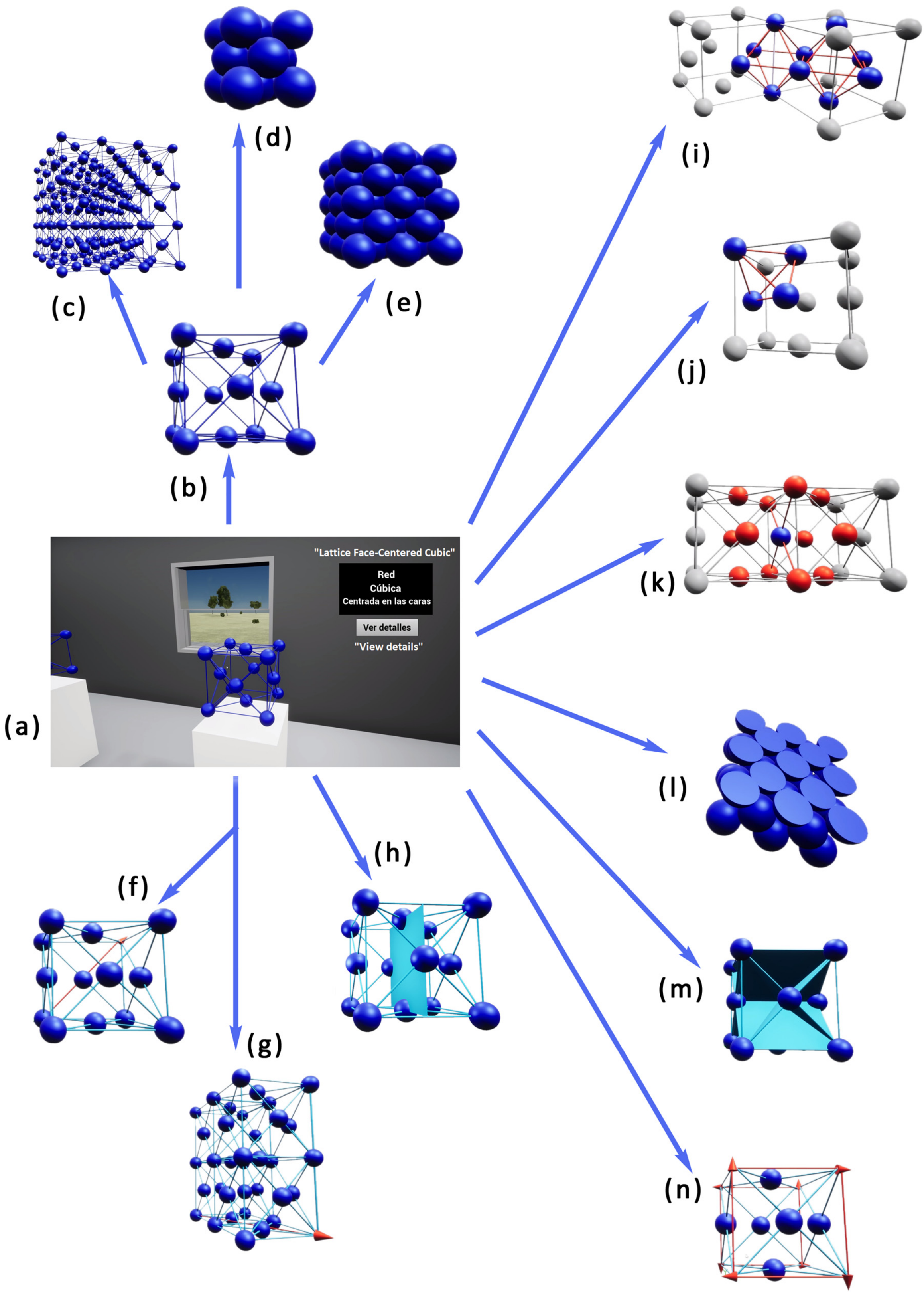

Figure 4. Different views of a material structure available in the VRLE showing: (**a**) lattice FCC; (**b**) expanded unit cell; (**c**) expanded set; (**d**) unit cell in CPK mode; (**e**) super set in CPK mode; (**f**) crystallographic direction [011]; (**g**) crystallographic direction [210]; (**h**) crystallographic plane [020]; (**i**) octahedral interstitial sites (voids); (**j**) tetrahedral interstitial site (void); (**k**) coordination index; (**l**) cross-section; (**m**) family of planes {110}; and (**n**) family of directions <100>. In part (**a**) the translation of text in Spanish to English is indicated inside the image.

This VRLE has been developed considering the results obtained from previous studies carried out by Vergara et al. [29,34–36]. These investigations detail: (i) the methodology that must be followed to create a VRLE, use it in the classroom, evaluate it, and subsequently improve it [29,34,35], and (ii) factors that must be taken into account to achieve a high degree of effectiveness at the formative level [34,36]. A flowchart is shown in Figure 5, which summarizes the steps followed to develop and implement such a VRLE in the classroom.

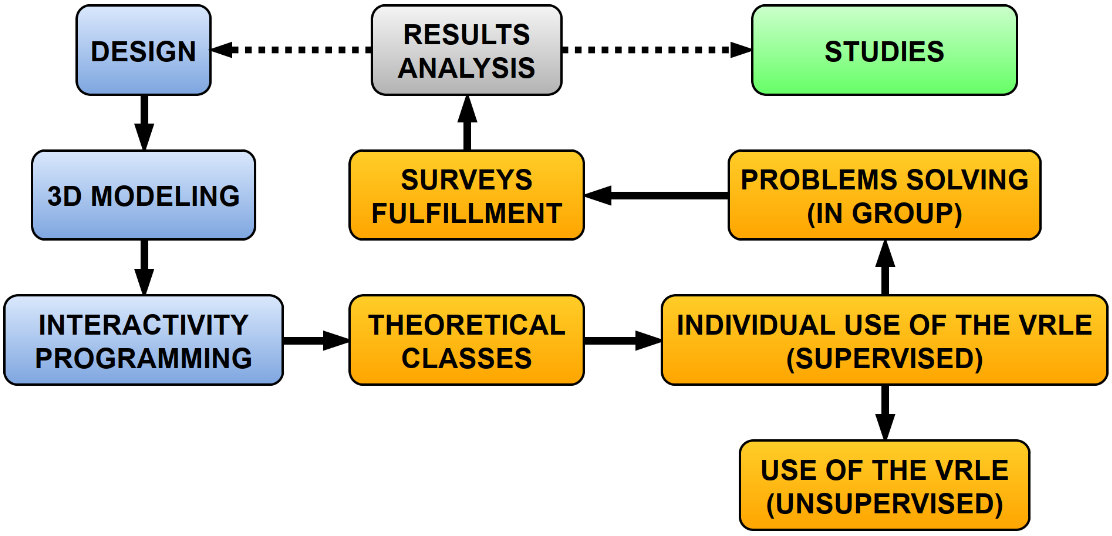

Figure 5. Summary of the methodology followed during the development of the VRLE and its implementation in the classroom.

4.1. Development

The first stage of development has consisted of defining in detail the design parameters of the VRLE, which are summarized as follows:

- what concepts it intends to teach: all those related to the teaching of Bravais networks at the university level
- what type of VR technology to use: NIVR
- what hardware will be necessary to run the application: mid-range PC
- how the user will interact with the application: keyboard and mouse
- what form of virtual environment: a museum (Figure 3)
- way in which the user will learn the concepts: approaching each stand of the museum and selecting one of the different options that are provided (cf. Supplementary video).

The next stage of development has been to three-dimensionally model the virtual environment and all its associated elements. At this stage, materials and textures have also been applied to the different virtual elements and the different stages have been illuminated. To carry out this activity, a recent version of 3DS Max® (version 2019, Autodesk, San Rafael, CA, USA, 2018) has been used. An important advantage of this program is the availability of a large amount of open access (at no cost) information on the internet about its management, as well as the solution to possible problems that may arise during its use.

The last phase of development consists of providing the virtual environment and the elements it contains with the interactivity necessary to be able to use it. In this stage, the following is programmed, among others: how the user moves around the stage, buttons that appear on the screen, actions that can be carried out on crystallographic networks or automatic movements (e.g., opening doors), etc. To carry out this programming, a recent version of the Unreal Engine 4® game engine has been used (UE4, version 4.21, Epic Games, Cary, NC, USA, 2018). UE4 uses object-oriented programming and allows the user to program a large number of functionalities using visual scripting, which avoids the need to write code, thus saving programming time (however, UE4 also allows the user to program more complex functionalities by typing C++ code). Additionally, UE4 incorporates advanced features in generating the visual appearance of virtual environments, such as physically-based rendering materials, realistic lighting effects indoors and outdoors, and latest rending techniques such as real-time ray tracing that uses calculation algorithms based on the laws of optics. This results in visually more realistic environments.

4.2. Use in the Classroom

The use of VRLE in the classroom is currently being implemented in the Materials Science and Engineering classes received by second-year Mechanical Engineering students at the Catholic University of Ávila (Spain). At first, the instructor gives master level courses (2–4 h) in which he/she explains the Bravais networks theory. At the end of these courses, students individually use the VRLE in the classroom under the supervision of the instructor for 30–60 min, and are able to continue using it unsupervised outside school hours as long as they wish. Subsequently, students formed teams of 2–4 individuals to solve an exercise for approximately two hours. Finally, the students filled out surveys from which the researchers extracted data whose analysis allows to understand, among others, the following aspects of the VRLE: (i) training effectiveness, (ii) acceptance by the students, and (iii) aspects of the program that require improvements.

5. Discussion

Through the systematic literature review carried out in this work, a total of 12 platforms of this type have been identified, which have been developed in 25 years. On the other hand, it is observed that all the platforms described (except for [51]), exploit the 3D visualization possibilities offered by VR and AR to help understand the arrangement that atoms and molecules have in space. It is also observed that, in most of the platforms, the focus is on teaching at least the unit cells, with the BCC, FCC, and HCP type being the most treated. Furthermore, IVR technology has been used almost as much as NIVR (three platforms use the first, four use the second, and two use both (Figure 2)), while AR has been used on three platforms. Finally, it is observed that eight of the 12 analyzed works include some type of study to evaluate the training effectiveness of the platform or to find out the opinion of the students.

Still, the main virtual laboratories dealing with this topic in the last years are described in this paper. Given the limited evidence of the use of these new technologies (VR and AR) in the field of crystallography, authors consider that the potential of such technologies is being little exploited in the education sector. On many occasions, it may be because to design this type of VRLE, a multidisciplinary team is necessary in which some dominate the knowledge of the subject (in this case, crystal lattices) and others the programming and development part in VR or AR. Nonetheless, these technologies are being used every day in more sectors (medicine, engineering, biology, education, etc.) given that, in many cases, they solve difficult situations facing other resources: space, cost, danger associated to certain experiments, etc. [57,58]. In the case of crystal lattices, the main problem that the VR or AR can solve is the spatial comprehension, since not only does the student have difficulties in spatially understanding these concepts, but the instructor may also have difficulties in explaining crystallographic networks if they do not have some didactic resource for it. In this sense, the authors' experience using the VRLE presented in this paper in the classroom is satisfactory for both the instructor and the students, which corroborates the experiences evaluated in previous works in this same sector [40–52].

6. Conclusions

In this article, a systematic literature review (SLR) has been carried out to check which applications based on virtual reality (VR) or augmented reality (AR), both virtual reality learning environments (VRLEs), have been developed to date in the academic field to support the teaching of concepts related to crystallography. The results obtained by the SLR allow to observe that, despite the current expansion of both VR and AR in many fields, in the environment of crystallography teaching, there are still few works carried out with these technologies. Likewise, within crystallography, it can be seen that projects based on both immersive VR and non-immersive VR have been practically the same, with AR being the least used technology so far. Despite the limited expansion of VR and AR technologies in the educational field of crystallography, surely due to the difficulty of having a multidisciplinary team to carry out the design of a VRLE, all the experiences reflected in the SLR presented in this article are positive since VRLEs help both instructors and students to better face the problems of spatial vision in the teaching-learning process of crystallographic networks. As technology continues to advance, future efforts are needed in developing further interactivity and to reduce the cost to make these systems more accessible, as well as in expanding different and easy-to-use teaching tools (e.g., e-books, in the cloud, etc.) for enhanced implementation in the class and curriculum development.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4352/10/6/456/s1, Video S1: Virtual and Augmented Reality Environments to Learn the Fundamentals of Crystallography—Demonstration of User Experience.

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Nomenclature

AR	Augmented Reality
BCC	Body-centered Cubic
CAVE	Cave Automatic Virtual Environment
CCDC	Cambridge Crystallographic Data Center
COD	Crystallography Open Database
DC	Diamond Cubic
FCC	Face-centered Cubic
HCP	Hexagonal Close-packed
HMD	Head-mounted Display
ICT	Information and Communications Technology
IVR	Immersive Virtual Reality
MEMS	Micro-electro-mechanical Systems
NIVR	Non-immersive Virtual Reality
PC	Personal Computer
SLR	Systematic Literature Review
SMA	Shape Memory Alloy
STEM	Science, Technology, Engineering and Mathematics
TEM	Transmission Electron Microscope
UE4	Unreal Engine 4®
VR	Virtual Reality
VRLE	Virtual Reality Learning Environment
WOS	Web of Science

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11. Aprendizaje Significativo mediante Entornos de Aprendizaje Basados en Realidad Virtual: Un Estudio de Caso en Ingeniería de Materiales

Existe una tendencia creciente a utilizar VRLEs en la enseñanza universitaria que persiguen mejorar el aprendizaje de los estudiantes de asignaturas de MSE. Una muestra de ello se encuentra en el hecho de que hasta la fecha se han publicado diferentes trabajos académicos centrados en el desarrollo de VRLEs que permiten simular ensayos de materiales, llevar a cabo análisis microscópicos, visualizar redes cristalográficas o estudiar los nanomateriales y los diagramas de fase, entre otros. En este sentido, la literatura científica reporta varios beneficios educativos asociados al uso de VRLEs en la enseñanza de MSE, así como una mayor motivación de los estudiantes (la cual está asociada a una mejora del proceso de enseñanza-aprendizaje).

El aprendizaje significativo se refiere a la idea de que un conocimiento adquirido es plenamente comprendido por un individuo cuando posteriormente es capaz de utilizarlo para establecer conexiones con otros conocimientos previamente aprendidos. En relación con este concepto, existen reportes de profesores que señalan que no todos los VRLEs logran el mismo nivel de aprendizaje significativo entre los alumnos que los han empleado. Teniendo en cuenta que el diseño de un VRLE desempeña un papel fundamental en el proceso de enseñanza-aprendizaje, los profesores se enfrentan al problema de no saber qué factores deben tener en cuenta a la hora de desarrollar sus VRLEs para conseguir con ellos un alto nivel de aprendizaje significativo de sus estudiantes. Por este motivo, el objetivo principal de este trabajo es comparar diferentes diseños de VRLEs para dilucidar cuáles de sus características resultan determinantes para lograr un alto nivel de aprendizaje significativo.

Al comparar un primer grupo de VRLEs (que fueron creados algunos años atrás) con un segundo grupo de VRLEs (que fueron creados recientemente) es posible apreciar que los primeros presentan un aspecto más anticuado que los segundos, lo que puede conducir a que los alumnos sientan menor motivación a utilizarlos ya que los perciben como “obsoletos”. El primer grupo de VRLEs se desarrolló con Quest3D y versiones que hoy son antiguas de 3D Studio Max. Por otro lado, el segundo grupo de VRLEs fue desarrollado mediante Unreal Engine 4 y versiones actuales de 3D Studio Max. Esta diferencia en el software de desarrollo empleado ha dado como resultado que los VRLEs del segundo grupo presenten, en relación con los del primer grupo: (i) mayor realismo gráfico; (ii) mejores posibilidades de interactividad; (iii) simulación de fenómenos físicos en los experimentos (p.ej., colisiones entre objetos sólidos); y (iv) facilidad de desarrollo y actualización en múltiples plataformas. Dado que estos factores influyen en el nivel de motivación de los estudiantes, se puede afirmar que los VRLEs diseñados con software actualizado son más atractivos que los VRLEs desarrollados con software más antiguo.

No obstante, atendiendo a los reportes de profesores, el proceso de desarrollo de VRLEs seguido hasta el momento no asegura que los estudiantes alcancen un nivel de aprendizaje significativo adecuado. Por ello, en este artículo se recomienda emplear un proceso de desarrollo de VRLEs en el que se incluye un protocolo de guiado paso a paso en aquellos casos en que se simulen experimentos de laboratorio. Esta recomendación implica que este tipo de VRLEs debería cumplir con los siguientes criterios: (i) ofrecer un nivel de interactividad suficiente para llevar a cabo el experimento virtual de forma motivadora y efectiva a nivel formativo (es decir, si el nivel de interactividad es bajo, el usuario no interactúa con el VRLE y no retiene el conocimiento; sin embargo, si el nivel de interactividad es excesivamente alto, el estudiante puede perder el hilo del experimento y desmotivarse); (ii) indicar al usuario cuál es el siguiente paso y cómo completarlo; y (iii) no permitir al usuario llevar a cabo acciones innecesarias ni que le conduzcan a arruinar el experimento virtual. La finalidad de implementar un protocolo de guiado paso a paso en un experimento virtual es ayudar al usuario a centrarse en la comprensión de cada etapa del experimento, evitando la necesidad de dedicar un tiempo excesivo a aprender a utilizar el VRLE. En cambio, cuando el objetivo de un VRLE es ayudar al alumno a comprender un concepto básico, se plantea escoger un nivel de interactividad que se encuentre entre estos dos extremos: (i) implementación de un protocolo paso a paso que restrinja de manera significativa la libertad de acción del usuario; y (ii) implementación de un mundo abierto, que permita al usuario explorar libremente con un alto grado de libertad de acción. El proceso de desarrollo planteado en este trabajo también tiene en cuenta la cantidad de información que se muestra al usuario mientras utiliza un VRLE. Esta información es principalmente de tres tipos: (i) instrucciones; (ii) información de ayuda; y (iii) información acerca de conceptos.

La metodología empleada para implementar en el aula cada uno de los VRLEs descritos en este trabajo ha seguido esta secuencia:

1. Impartición de clases teóricas en el por parte del profesor.
2. Uso individual del VRLE por parte de los estudiantes.
3. Resolución de ejercicios en pequeños grupos de alumnos.
4. Un año después de emplear el VRLE, los estudiantes respondieron cuestionarios relacionados con los conceptos aprendidos con ayuda de dicho VRLE.

El uso y evaluación de los VRLEs se ha llevado a cabo durante los cursos académicos comprendidos entre 2014 y 2019, participando anualmente alrededor de 20 alumnos de asignaturas de MSE del grado en Ingeniería Mecánica de la Universidad Católica de Ávila (España). Nótese que los primeros alumnos que participaron en el estudio usaron VRLEs en 2014 y respondieron los cuestionarios en 2015, mientras que los últimos participantes usaros VRLEs en 2018 y respondieron los cuestionarios en 2019. Los resultados obtenidos de las respuestas de los cuestionarios apuntan a que aquellos estudiantes que emplearon VRLEs diseñados según el proceso propuesto en este trabajo y empleando programas de desarrollo actuales obtuvieron calificaciones más altas (es decir, recordaron por más tiempo lo aprendido mediante el uso de los VRLEs).

En conclusión, en este estudio se ha puesto de manifiesto que desarrollar VRLEs con programas actuales favorece la motivación de los estudiantes, lo cual redunda en que se sientan comprometidos y centrados en los contenidos del VRLE. A su vez, se ha hallado que el factor clave que contribuye de manera determinante a aumentar el nivel de aprendizaje significativo de los alumnos es la inclusión de un protocolo de guiado paso a paso en el proceso de desarrollo de aquellos VRLEs destinados a simular un experimento de laboratorio.

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Meaningful Learning Through Virtual Reality Learning Environments: A Case Study in Materials Engineering

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Featured Application: The key characteristics that a virtual reality learning environment (VRLE) must have to support an appropriate level of meaningful learning in higher education are detailed in this paper.

Abstract: The increasing dissemination of virtual reality learning environments (VRLEs) compels the elucidation of how these didactic tools can improve their effectiveness at the formative level. The motivation generated in students by a VRLE is revealed as a key factor in achieving meaningful learning, but such a motivation by itself alone does not guarantee the long-term retention of knowledge. To identify the necessary characteristics of a VRLE to achieve an appropriate level of meaningful learning, this paper compares a set of VRLEs created in previous years with a group of recently developed VRLEs, after being used by engineering students. A description of the design process of the both VRLEs groups is included in this paper. Most significantly, analysis of the response of a total of 103 students in a specific survey reveals how a step-by-step protocol system helped improve students' knowledge and retention after one year of using a VRLE. Thus, this study not only demonstrates the importance of using modern development engines when creating or updating a VRLE to achieve student motivation, but also justifies in many cases the use of a step-by-step protocol as a method to improve the long-term retention of knowledge.

Keywords: virtual laboratory; virtual reality learning environment; meaningful learning; design; materials science and engineering.

1. Introduction

There is a growing trend to use virtual reality learning environments (VRLEs) in education to enhance the student learning process and course learning outcomes [1]. This fact is also reflected in the instruction of materials science and engineering (MSE) in higher education [2,3]. To date, different tests of materials have been simulated in a VRLE (e.g., tensile testing [4,5], compression testing [6], impact testing [7,8], hardness testing [7,8], microscopic analysis [7,8], and non-destructive testing [9,10]). In addition, other key aspects related to MSE have been investigated in a VRLE (e.g., crystal lattices [11,12], phase diagrams [13,14], nanomaterials [15,16], and materials manufacturing processes [17]). Several educational benefits of implementing virtual reality (VR) in MSE have been reported in the literature [4,18,19]. The most important of these benefits are related to the fact that

VRLEs: (i) solve the shortcomings linked to overcrowded practical classes; (ii) provide a means to complement student learning experience, given the limited materials testing machine handling time per student in a traditional classroom or laboratory; (iii) offer high-quality visualizations which are not readily feasible in the traditional classroom; (iv) allow instructors to develop ad hoc didactic applications in the virtual environment for reinforcing acquired knowledge; (v) increase students´ engagement and motivation in almost any field of study by bringing them closer to a friendly and familiar environment; (vi) improve the quality of education in varied disciplines; (vii) help reduce the cost associated with modern laboratory classes; and (viii) decrease the potential risk of physical harm of students during the handling of real materials testing machines. Furthermore, a better teaching–learning process has been recognized in several research studies [20–22], leading to better understanding and higher motivation, among other benefits. Despite these advantages, the use of VRLEs in MSE also presents some potential risks, for instance: (i) the user usually feels safe, without realizing the dangers of handling certain types of real machinery [23]; (ii) the student often shows a lack of seriousness, responsibility and care when conducting an experiment in the VRLE [23], which means that the training effectiveness can be reduced; and (iii) the relation between the design of the VRLE and various pedagogical aspects (motivation, ease of use, educational usefulness) may vary over time, forcing the teacher or trainer to keep the software up to date [1,24].

It is particularly worth noting that the design of a VRLE plays a key role in the development of the teaching–learning process [11,24,25]. In fact, according to previous findings, "a direct relationship exists between the virtual tool design and the motivation generated in the user to keep on using it" [11]. Among the challenges of using VRLEs in the classroom include the fact that they: (i) can affect the personal student communication and interpersonal connections in a traditional class if a pedagogical implementation is not carefully designed; (ii) can exhibit lack of flexibility compared to a typical classroom experience where a student can ask questions and receive answers and clarifications (this issue can be addressed by designing more complete pedagogical materials with protocols from instructors); and (iii) can be costly as with other advanced technologies, however rapidly changing markets offer more affordable tools, thus VR will increasingly be used in learning, training, and fostering collaborative projects.

The latest advances in the field of VR are related to the users' immersion in the virtual environment [26–29], which is known as immersive virtual reality (IVR). However, such technology has not yet reached higher education and only a few isolated examples exist to date. There are varied applications based on IVR that can create and explore fullerenes molecules [30], investigate the case study of pneumatics [31], and observe fully programmed robotic manipulators [32], to name but a few. IVR makes use of head-mounted display (HMD) technology, with newer projects that include the CAVE (cave automatic virtual environment) system [33,34]. Forgarty et al. [35] have reported a recent application to improve student understanding of complex spatial arrangements using VR. Furthermore, there is an increasing growth in applications based on augmented reality (AR). For instance, Dinis et al. [36] have recently described how to improve the learning in civil engineering by focusing on building construction. Besides, there are contemporary studies comparing the effectiveness in learning when using VR, IVR, and traditional methods. Indeed, more recent studies [37] have confirmed that when students use VR in a learning setting, they are more engaged and are more motivated compared to when they use conventional tools such as slide presentations via PowerPoint. In contrast, some investigators [38] have found little or no difference in the learning effectiveness when comparing non-immersive VR and IVR, whereas the learning is reported effective in both cases.

Meaningful learning refers to the idea that a learned knowledge (or fact) is fully understood by an individual who can then use it to make connections with other previously known knowledge. Based on the authors' experiences in using technology enhanced learning (TEL), not all VRLEs support the same level of meaningful learning experience and a VRLE may even be attractive to users but not effective at the formative level. Thus, teachers currently face the problem of not knowing what key factors are to be considered when creating or designing their VRLEs in order to achieve a high level of meaningful learning. Furthermore, to the authors' knowledge, there is no publication to date covering the influence of VRLEs' design on meaningful learning. Thus, taking into account the research trajectory of the authors, who have recently designed and implemented several virtual laboratories based on VR and IVR technology in the field of MSE [2,4,6,9–11,14–16,24,39–41], the main objective of this paper is to compare different VRLE designs to elucidate the most suitable features for achieving meaningful learning. Consequently, key factors that a TEL-based VR must have to promote a good level of meaningful learning experience in the classroom are described in this contribution. The implications of the present study are not limited to the field of MSE but are applicable to any other discipline that could readily benefit from using VR or IVR (e.g., biology, chemistry, bioengineering, and medicine).

2. Virtual Reality Learning Environments

In the past few years, several VRLEs have been utilized in the classroom and for training in the field of MSE. These systems have been described in detail in previous articles [4,6,9,11,40] and, given the fast pace of technology development, they could be considered "obsolete"—although they were created only about five years ago—and, consequently, relatively "undesirable" to students (Figure 1). Despite this, it is the authors' experience that these VRLEs have always been well received by students and, therefore, they can be compared with newer VRLEs that the authors more recently designed with modernized VR technology—some of them described in recent papers [11,41]—(Figure 2).

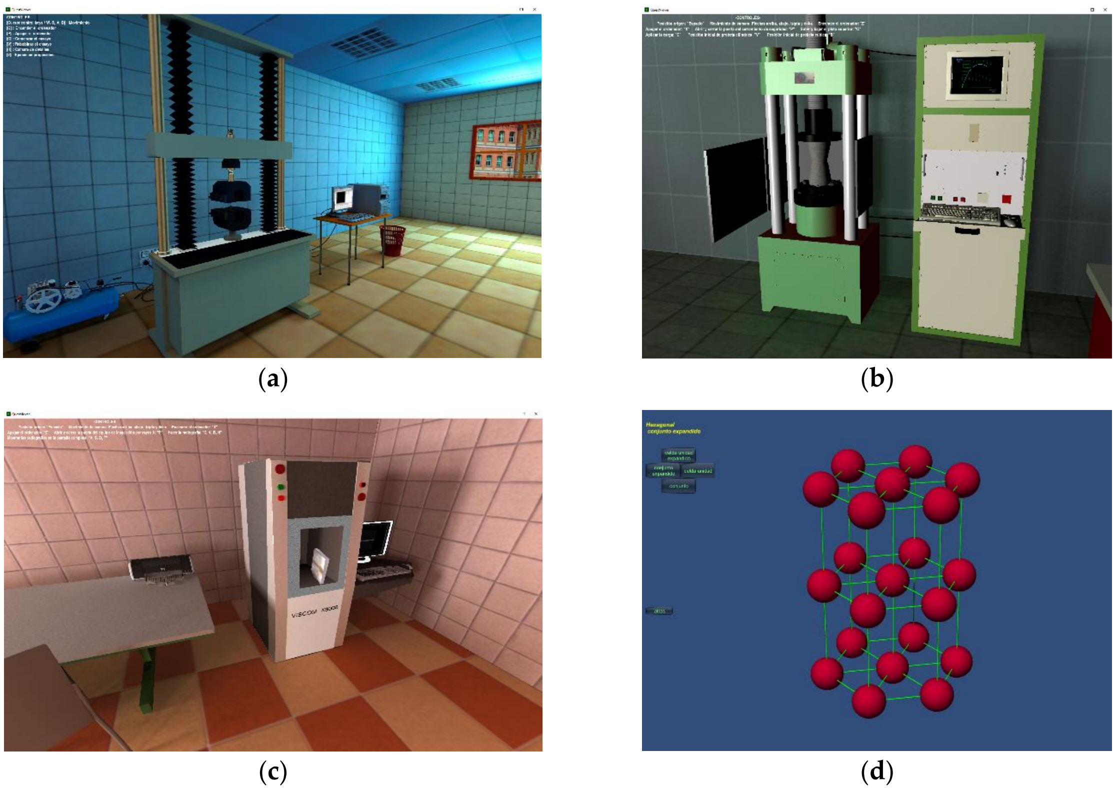

Figure 1. Representative virtual reality learning environments (VRLEs) designed with virtual reality (VR) software several years ago: (**a**) tensile testing; (**b**) compression testing; (**c**) X-ray evaluation; and (**d**) crystal lattices simulation.

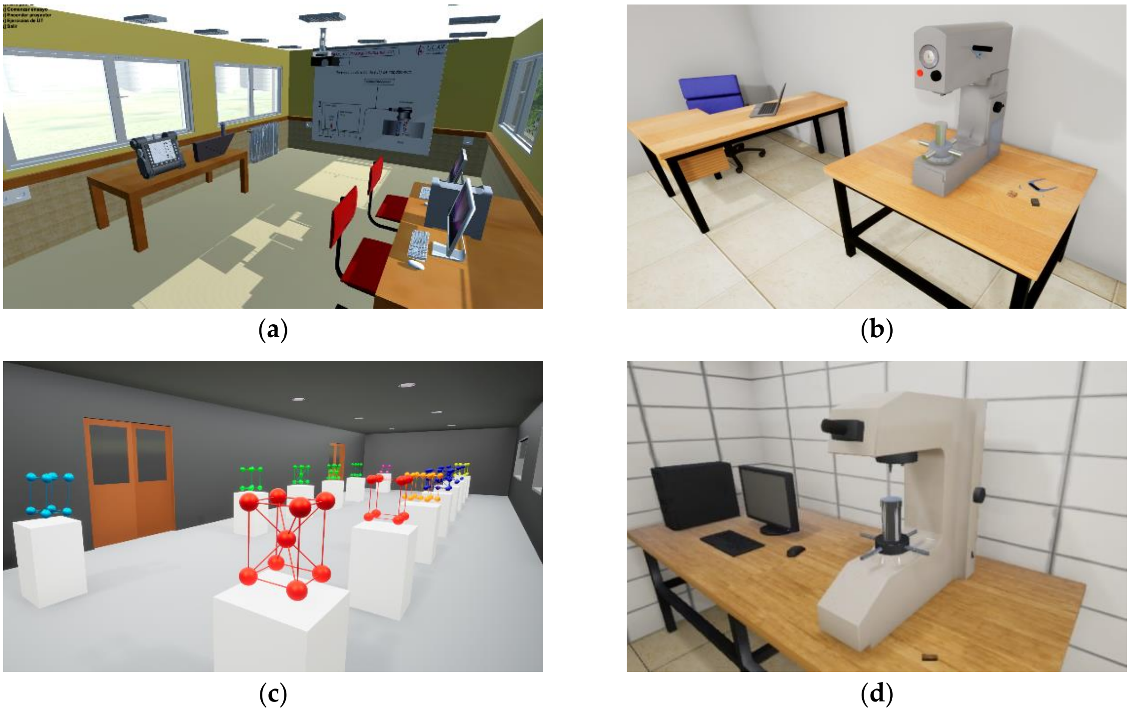

Figure 2. More recent VRLEs designed with newer VR software: (**a**) ultrasonic testing; (**b**) Rockwell hardness testing; (**c**) crystal lattices analysis; and (**d**) Vickers hardness testing.

Regarding the VRLEs depicted in Figure 1, the VR software used was Quest3D in several of its versions, which is the combination of a video game engine with a development platform where interactivity is programmed. Models and environments were initially created with older versions of Autodesk 3D Studio Max software, which offered limited possibilities. The Quest3D software was generally used for architecture, product design, video games, training software, and simulators (nowadays, this software is often used for video games). Among the key limitations of Quest3D are that it: (i) does not generate realistic results since it does not account for the physical–chemical characteristics of the interaction of light with a material surface; (ii) does not simulate particle or dynamic systems such as liquids, collisions, and fractures; (iii) does not allow creating immersive virtual reality environments; and (iv) demands a greater specialization in programming.

By contrast, the software used to design the 3D scenes of VRLEs, shown in Figure 2, were Autodesk 3D Studio Max (current versions) and Epic Unreal Engine 4 (UE4) for programming. UE4 is a new creation tool, much more powerful than Quest3D, which was designed for a less expert user and has enhanced photorealistic graphic results. In efforts to improve the performance of VRLEs, 3D environment modeling tasks were performed separately from programming tasks for interactivity via two general types of specialized programs for distinct purposes:

- Modeling software and 3D animation: dedicated programs were used to create three-dimensional virtual environments. These are the same software as those used in the production of current films, video games, and projects and previews of engineering and architecture. Although other software alternatives were available (Cinema 4D, Autodesk Maya, Blender, etc.), Autodesk 3D Max (v. 2018) was selected in the design of VRLEs shown in Figure 2.
- Game engines: originally created for video game programming, these engines are responsible for generating interactive images of a video game or an IVR application. These tools provide a rendering engine to generate: (i) 2D and 3D graphics; (ii) an environment that detects physical collisions between objects; and (iii) visualization of the responses to those collisions, interaction with the environment, realistic materials physically based rendering (PBR), lighting with bounces, raytracing, sounds and music, animation, artificial intelligence, communication with the network,

multi-users, memory management, etc. Another important feature is the possibility of developing different platforms and technologies for: (i) Android and iOS mobile devices; (ii) desktop computers including Windows, Macintosh, HTML5, and Linux; and (iii) consoles such as PlayStation, Nintendo Switch, and Xbox One. Although several options were available (e.g., Unity and CryEngine), UE4 was selected for the design of enhanced VRLEs shown in Figure 2.

The use of UE4 software allows creating much more realistic VRLEs, with greater possibilities of interaction, and IVR environments. UE4 is a virtual reality engine that allows programming in two different ways: (i) coding in C++ language; and (ii) using the Blueprints Visual Scripting (BVS) system. The programming mode used in the newer VRLEs (Figure 2) is BVS, which is a graphical programming system based on object-oriented programming (OOP) that does not require coding. Programming using the BVS system saves considerable time compared to programming by coding. Although certain functionalities can only be programmed by writing C++ codes, all the interactivity of the VRLEs developed more recently (Figure 2) has been achieved exclusively via the BVS system.

Regarding BVS, two key components are emphasized next: (i) blueprints, which are the basic programming units from which the objects characterizing the OOP are created; (ii) graphic programming board, corresponding to each blueprint. Each blueprint is programmed using its own graphic programming board: on this board are placed pre-configured nodes that define specific functionalities (e.g., read the spatial coordinates of an item contained in the 3D scene). Each node is connected to other nodes by means of wires, thus establishing a relationship between them.

There are numerous blueprints available in UE4 oriented to a broad range of functionalities. However, VRLEs in Figure 2 have mainly required the use of the following types of blueprints:

- Level: contains the main code, from which key elements (user inputs, movement of objects and cameras, and the show-and-hide of interfaces, buttons and help elements) are created.
- Character: establishes the avatar that the user controls.
- Game Mode: defines a centralized repository of variables required by other blueprints.
- Player Controller: specifies aspects of user control.
- Widgets: position the interfaces that allow displaying of buttons and messages.
- Actors: allow the use of objects in a given scene with advanced functionalities.

Usually the needs that arise during programming are met through nodes with trivial functionalities. However, there are circumstances that require specific combinations of nodes that are not always easy to infer or find either in specialized literature or in the wide range of developer forums available on the Internet.

Due to the increasing power and accessibility of computers, and the relentless evolution of the development of 3D modeling tools, the current VRLEs present a series of important improvements. To effectively compare VRLEs shown in Figure 1 (5 years ago) and Figure 2 (more recent), the main technical features are summarized in Table 1. Several advantages are evident in the newer VRLEs: (i) higher graphic realism; (ii) better adaptation to the interactivity level established in the design criteria of the application; (iii) simulation of physical phenomena in experiments, such as collisions; and (iv) easiness of development and updating on multiple platforms, including those based on IVR. The importance of such characteristics in a VRLE has been thoroughly discussed in previous studies [1,2]. Since these traits influence the level of students' motivation [24], the VRLEs designed with updated software (Figure 2) are found to be more engaging than older versions (Figure 1), despite having only about five years difference between them.

Table 1. Comparison of main characteristics of VRLEs developed by the authors at different stages.

Feature	VRLEs (5 years ago) Figure 1	VRLEs (updated) Figure 2
• Light bounces according to optic equations	No	Yes
• Realistic physically based rendering materials	No	Yes
• Virtual environment subject to laws of physics	No	Yes
• Easy adaptation to platforms other than the computers	No	Yes
• Possibility of adaption to immersive virtual reality (IVR)	No	Yes
• High knowledge in programming required for development or updates	Yes	No

3. Design Considerations of a VRLE

Prior studies [1] have reported that the development of a VRLE should be carried out following a design process (Figure 3) that involves steps to: (i) decide the level of realism required to achieve the objectives of the VRLE; (ii) choose the level of interactivity for the VRLE; (iii) select the software and hardware that best suits the development needs arisen from the previous steps; (iv) simulate the virtual environment and program the interactivity; and (v) test the application with pilot users and make the required modifications upon analysis of the results from such tests.

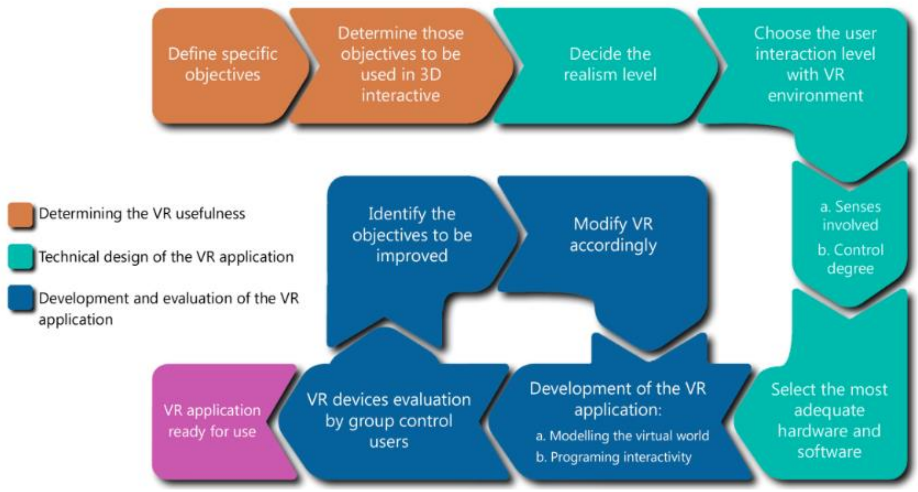

Figure 3. Design process of a VRLE previously described and published elsewhere.

Nonetheless, based on the authors' own experience, the design process shown in Figure 3 does not guarantee the achievement of meaningful learning. Thus, we recommend in this article to include a robust step-by-step protocol in the design process of those VRLEs that simulate realistic laboratory experiments. In fact, the concept of a step-by-step protocol for a VRLE implies that it meets the following criteria: (i) displays a sufficient level of interactivity to carry out the virtual experiment in a motivating and effective way at the formative level (i.e., if the level of interactivity is low, the user does not interact with the VRLE and does not retain knowledge; however, if the interactivity is too high, the user can lose the thread of the experiment and become unmotivated); (ii) always indicates to the user what is the next step to take and how to complete it; and (iii) does not allow the user to carry out unnecessary actions or lead the user to fail the experiment. The step-by-step protocol of a virtual experiment hence helps the user to focus on understanding each stage of the experiment, avoiding the need to spend a lot of time learning how to use the VRLE [41]. Figure 4 shows the result of adapting the step-by-step protocol to the prior flow chart of Figure 3.

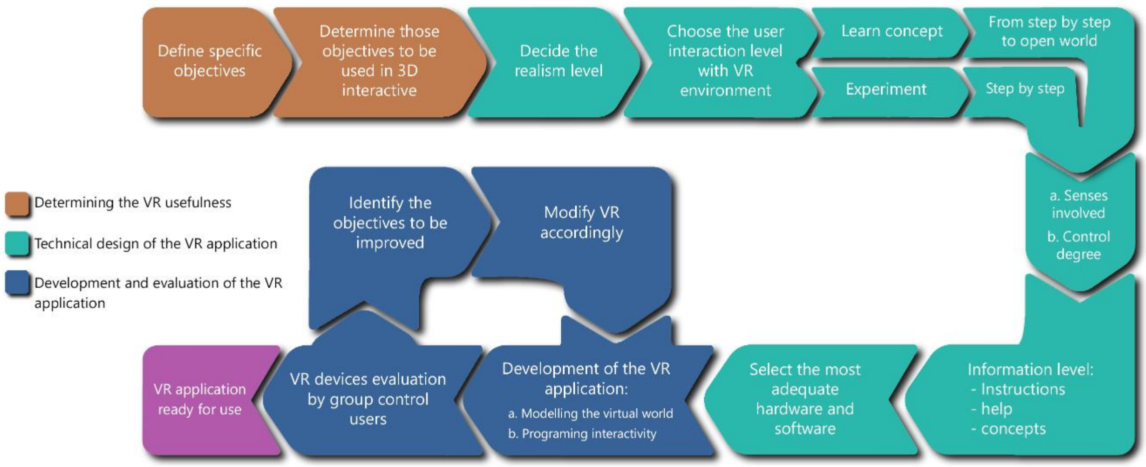

Figure 4. A newer design process, including a step-by-step protocol, as described in this publication.

The main difference between both flow charts (Figures 3 and 4) is the level of attained interactivity which will vary depending on the aim of the VRLE, namely to: (i) help the user to learn how an experiment shall be carried out, or (ii) help the user to understand a concept. When a student conducts an experiment in a real laboratory, before starting the actual test, he/she receives a procedure from the teacher that contains a detailed sequence of steps that the student must follow from beginning to end, for successful completion of the test. Similarly, a student who performs a virtual experiment in VRLEs that simulate real experiments (by means of a step-by-step protocol) should receive the same detailed steps that the student would follow in a real laboratory. By contrast, when the objective of the VRLE is to help the student to understand a basic concept, different levels of interactivity can be chosen for distinct scenarios: (i) a step-by-step approach, which would allow little freedom of action; (ii) an open world, which would allow the student to freely explore with a high degree of freedom. Another difference between Figures 3 and 4 is the amount of information that is displayed to the user while using a VRLE. This information is mainly of three types: (i) instructions; (ii) help information; and (iii) conceptual information. The former refers to information that tells the user how to use the application (e.g., what options are available, what steps shall be followed, how to use the controls). The second refers to information that is shown when the user makes a mistake or when he/she asks for help when facing problems to continue using the application. The third case refers to information that clarifies concepts related to the experiment itself or concepts studied through the VRLE.

Based on the development process outlined in Figures 3 and 4, we focus on the fact that before starting the development of a VRLE, two requirements must be met [1]: (i) the tool to be developed must improve the teaching–learning process; and (ii) the effort required to develop the tool must be justified, which will depend essentially on the advances in computation at that moment. Regarding this last point, it can be inferred that before starting the development of a VRLE it is very important to know the following data of the technology to be used: (i) availability in the market where the VRLE is to be developed; (ii) dissemination in universities and target students; and (iii) current price. For example, the development of a VRLE that requires a high-range HMD system would not be justified in a developing country because: (i) the necessary hardware cannot be acquired since it is often scarce or not available; (ii) the technology is not widespread in universities or among students in those countries; and (iii) the acquisition likelihood by universities or students in these countries is almost impossible due to its high cost. On the contrary, the development of such VRLE would be justified if it was designed to be used in a personal computer with medium or low computing capacity since these types of computers: (i) can be purchased in most cities; (ii) are currently widely spread in universities and among students; and (iii) are accessible and economical, and therefore their price would not stop their acquisition if necessary.

Further analysis of the flow charts of Figures 3 and 4 reveals that all aspects related to the technical design of an application (e.g., determination of the level of realism, determination of the mode of interaction, selection of hardware and software) are closely related to what has been previously exposed. In this sense, we noticed a straightforward correlation: the higher the budget of the hardware, the higher the level of realism and interactivity the VRLE can offer, but the dissemination among end users will be lower. By contrast, the smaller the budget of the hardware, the greater the dissemination of the VRLE but the lower its realism and interactivity, thus becoming an "undesirable" tool for the student.

4. Meaningful Learning Analysis

4.1. Problem Statement

The typical training involving an MSE machine is usually carried out with large groups of students, which hinders a good teaching–learning process [6]. A possible solution to this problem is the implementation of VRLEs. In the first case (a large group of students around an MSE machine) is logical to expect a less meaningful learning experience, but in the second case (an individual instruction though a VRLE) the expectation should be the opposite, i.e., students would undergo a highly meaningful learning experience. However, during the last five years using several VRLEs similar to those displayed in Figure 1, the authors have verified that students hardly remember how a real MSE machine works in the following year upon training. Even during subsequent visits to real laboratories, it was found that some students did not remember having handled virtually (through a VRLE) some of the machines that were in those laboratories the previous year. For this reason, through the analysis of the data obtained in this study it is intended to explain what factors are the most significant to explain this fact.

4.2. Methodology

The methodology used in the recent VRLEs described in this work (e.g., Figure 2) is divided as follows: (i) assume a theoretical class —the process will vary in time depending on the real machine desired to simulate; (ii) estimate the time for individual use of the VRLE, which may take approximately 10–15 minutes (besides, students can reuse the VRLE in their free time); (iii) determine the resolution of the virtual exercises for small groups (2–3 students) including the VRLE [4,9,10] or traditional classroom exercises (using paper); and (iv) collect individual fulfillment of an specific survey one year later, which contains technical aspects of the different VRLEs used the previous year (e.g., the students who handled the VRLE in 2014 completed the technical survey in 2015, which allowed to know the level of knowledge of MSE machines that they still remembered a year later). For the reader to get an idea of the type of questions that have been raised in the survey, some examples are shown in Table 2. Three questions of a total of 30 have been selected; through these questions the students are asked about concepts of MSE simulated through a virtual environment (e.g., tensile testing [4], compression testing [6,40], industrial radiology [9], ultrasonic testing [10], crystal lattices [11], ternary phase diagrams [14,39], and hardness testing [41]). Although Table 2 does not include all the questions, it should be noted that the survey questions were the same during all the years considered in the present study, hence ensuring that the results from different years are comparable.

For the sake of clarity, a scheme of the methodology followed in this study is presented in Figure 5. The implementation and evaluation of the VRLEs were carried out during the academic courses between 2015 and 2019. Students of MSE subjects of the degree in mechanical engineering taught at the Catholic University of Ávila (Spain) participated in this study. Each year approximately 20 students participated. During the first four years (2015–2018) the study was based on the VRLEs created with the design process shown in Figure 1, which were used by students the previous years (i.e., 2014–2017) to fulfil the student survey requirement. However, more recently, in 2019, the study was based on the new design process (step-by-step protocol), as illustrated in Figures 2 and 4. In this case, the students used the updated VRLEs from 2018, which were designed as shown in Figure 4.

Table 2. Examples of questions and answers included in our student surveys.

Question	Answers
• Which Rockwell scale would you use for a high strength steel?	(a) HRC (b) HRB (c) HR15N
• In a tensile test, what does UTS mean?	(a) Yield strength (b) Young modulus (c) Maximum strain (d) No answer is correct
• In Vickers hardness testing, what is the shape of the indenter?	(a) Hardened steel ball (b) Diamond in the form of a cone (c) Diamond in the form of a square-based pyramid

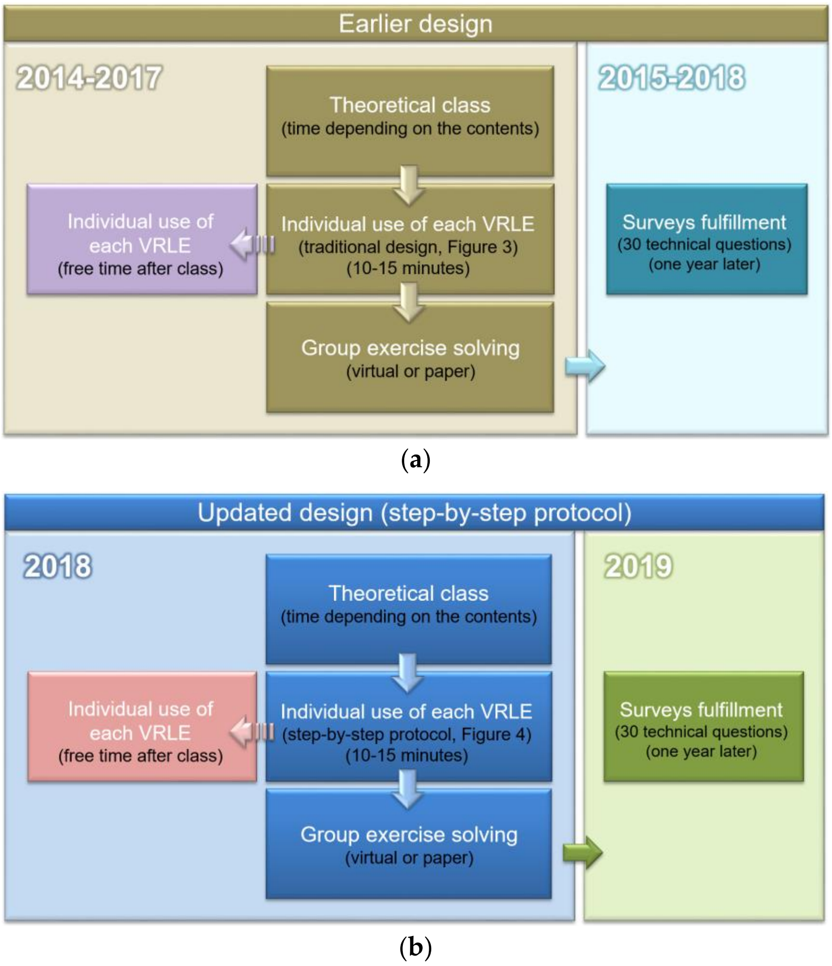

Figure 5. Schematic of the methodology followed in the present study: (**a**) during 2015–2018; and (**b**) in 2019.

To improve the retention of content, authors have decided to modify the design of the VRLEs by including a step-by-step protocol. Thus, the design process (and, specifically, the step-by-step protocol) is the main significant difference between the methodology used with the VRLEs of Figures 1 and 2.

4.3. Results

The improved VRLEs were implemented in a course within the Mechanical Engineering major, which covers MSE. One year after, these same students were enrolled in other classes focused on other topics related to industrial and manufacturing processes where several MSE machines are applied again (e.g., contents dealing with quality control). Since authors verified that many of the students did not remember how these machines work, they began doing surveys to assess quantitative data to measure the level of such knowledge. Some examples of the types of technical questions raised in the survey are shown in Table 2.

A summary of such data related to the concepts recalled by a total of 103 students (approximately 20 students each year) is shown in Figure 6. These results show the average value of the technical questions correctly answered by the students (students' marks), which reveals the level of knowledge they remembered about MSE machines and contents (which they studied one year prior to the survey through VRLEs). In addition, statistical variables of the survey results (the number of right answers), such as mean and standard deviation, were collected (Table 3).

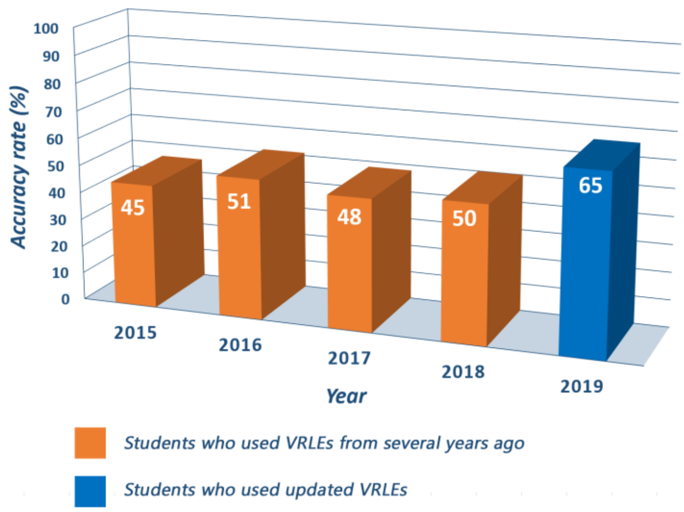

Figure 6. Accuracy rate (students' marks) of survey questions provided by students, who participated a year earlier in class sessions covering fundamental concepts in material science and engineering (MSE) through VRLEs.

Table 3. Statistical results of students' marks after using VRLE one year prior.

Students' Marks	2015	2016	2017	2018	2019
Mean (%)	45.33	51.33	48.41	49.84	64.76
Standard deviation (%)	6.93	7.60	7.50	7.11	11.23

5. Discussion

Clearly, it is practically impossible for all students to retain knowledge for a year without forgetting anything (i.e., to achieve 100% accuracy rate in Figure 6). In spite of this unrealistic expectation, both Figure 6 and Table 3 show that the percentage of retained knowledge varies from one year to another: between 2015–2018 there are hardly any differences, but there is an increase in 2019. The results from 2015–2018 are based on the use of earlier VRLEs designed several years ago (Figures 1 and 3), whereas the results obtained from 2019 are related to the use of updated VRLEs designed more recently (Figures 2 and 4). During the period 2015–2018 the accuracy rate varies between 45% and 51% (Figure 6), while in 2019 the mean value rises to almost 65%, thereby increasing approximately 30% over previous years. On the other hand, the standard deviation is quite similar in the period 2015–2018, indicating a non–significant variation from year to year (extending the number of right answers from 11 to 20 out of 30). However, the higher standard deviation in 2019 suggests a greater dispersion of results, emphasizing that the new design process (step-by-step protocol) is quite effective for some students but, at the same time, it is not too effective for others. Nevertheless, taking into account that the range of data in 2019 is between 13 and 24, it is possible to ensure that the new design favors a higher level of meaningful learning.

Several factors could influence these results: (i) the teacher; (ii) the contents given during class in the different years; (iii) the methodological process used during classes; (iv) the survey questions; (v) the academic level of the students; (vi) the software used to create the VRLEs; and (vii) the design process used in the VRLEs. Given that the first four factors have been the same during all years (2015–2019)—the teacher was the same during such a period, the contents did not vary from year to year, the methodological process was identical in all the academic courses, as shown in Figure 5, and the survey questions were the same in all cases)—and that the students' scores were similar as well, the key variables that may have had significant influence on the improved results in 2019 are: (i) the software used to create the VRLEs (i.e., newer, more powerful, and more versatile in 2019 than in 2015–2018, consequently, the VRLEs are more appealing and engaging for students [24]); (ii) the new design process used in the VRLEs in 2019 (Figure 4) with an enhanced step-by-step protocol.

It should be noted that updating a VRLE with a better realism helps the student to be more motivated, thereby being more engaged and focused on the contents of the VRLE (which likely leads to a higher level of meaningful learning). However, based on the authors' own experience in designing different VRLEs for several years, the more relevant aspect influencing the meaningful learning experience is the step-by-step protocol. In previous studies [4,6,9–11,15], the authors have verified that, in general, the motivation is always high when using this type of TEL. However, this aspect (higher level of motivation by updating the software) cannot be the key factor that has favored the increase reflected in Figure 6 of approximately 30% in the knowledge retained one year after. Taking into account that no significant differences are found when comparing the overall grades of students during the academic courses considered in this study ranging from 2015–2019, the higher level of motivation generated in students when using an updated VRLE should not have significative influence on the meaningful learning. Consequently, the more relevant aspect affecting meaningful learning via a VRLE should be the new design process including a step-by-step protocol.

In addition, the fact that students use a step-by-step protocol in an MSE virtual laboratory is much more effective at the didactic level than doing the practical classes in a real MSE laboratory, where usually only the instructor handles the machines. Prior studies have also reported the effective use of a step-by-step protocol to design interactive lessons via audio-visual e-books for MSE learning [42]. The authors have experienced throughout the years a better understanding of the contents at the time of using the VRLE and the need to improve the design process, which will lead to a higher level of student retention of such contents over time and thus meaningful learning.

There are certainly circumstances where VRLEs do not need a step-by-step protocol (e.g., when the simulated experiment consists of a single step or the VRLE is intended for understanding a basic concept) and the meaningful learning should be empowered in a different way. Therefore, in this scenario it is important to consider the graphical requirements (i.e., desirable visuals) and the use of VRLEs (e.g., new interactivity methods via IVR and haptic responses). In fact, since UE4 allows the design of VRLEs to be used in immersive environments (ranging from economic systems such as Google Cardboard to professional HMD systems such as HTC Vive Pro), future research on the influence of immersion level on meaningful learning is compulsory to better understand both the origin of the differences observed thus far and the promising ways to improve them.

6. Conclusions

Virtual reality learning environments are powerful and useful tools in the educational field as they can solve some of the typical problems that occur during practical classes in real laboratories, e.g., some students fail to see all details when a test or experiment is carried out (even when the student group is large, some of them cannot see anything from the experiment), other students cannot listen the technical explanation when the test is carried out, etc.

The advantages that a VRLE could present from a didactic point of view directly depend on the design process. A proposed design to improve the level of meaningful learning in a VRLE was presented in this paper. The design process includes a step-by-step protocol as a key component, which was corroborated in a five-year research by means of using different VRLEs in the field of materials science and engineering. Based on the results thus far, it is worth noting that the design process in a VRLE has an influence on the students' meaningful learning, much more than other aspects such as the software used to create the VRLE or others. Therefore, to ensure a better level of meaningful learning through the use of a VRLE, the authors recommend designing the didactic resource with a step-by-step protocol whenever possible, as they will provide optimum experience.

Furthermore, the amount of data being collected, recorded and stored routinely nowadays through VRLEs is increasing at a fast rate due to inexpensive computing, widespread use of electronic records, digitalization of imaging, storage capability, and rapid development of other technologies (e.g., augmented reality, artificial intelligence, machine learning). Therefore, future efforts will also rapidly increase to foster new cyberinfrastructures (i.e., network of VRLEs where users collaborate on projects remotely) to accelerate materials discovery, learning, and training of individuals seeking new skills (e.g., data science) and opportunities. This would require fast and specialized frameworks, efficient didactical methods designed for many disciplines, varied levels of interactivity, etc., in order to efficiently adapt to different team sizes, degrees of complexity, etc.

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12. La Obsolescencia Tecnológica de los Entornos de Aprendizaje Basados en Realidad Virtual

La obsolescencia tecnológica es un fenómeno que afecta a cualquier dispositivo que utilice algún tipo de programa informático ya que este último, generalmente, es sometido a diversos procesos de actualización. Una muestra de ello se encuentra en las continuas actualizaciones que los desarrolladores llevan a cabo sobre sus programas informáticos o los cambios que presentan las páginas web a lo largo de los años. La transformación en el uso del hardware hace que cambie su dominio de uso y sus aplicaciones. Por ejemplo, un teléfono móvil en los años noventa del siglo pasado se utilizaba principalmente para hacer llamadas telefónicas, mientras que un smartphone actual se utiliza para muchos otros propósitos. En respuesta a estos cambios, el software debe ser capaz de seguir el ritmo marcado por las necesidades de la sociedad ampliando y perfeccionando sus funcionalidades, corrigiendo fallos y mejorando su rendimiento, entre otros. La importancia del proceso de evolución del software se refleja en la gran cantidad de dinero que las empresas de desarrollo invierten en actualizar sus aplicaciones informáticas tras el lanzamiento de la primera versión. Por tanto, conocer el proceso evolutivo del software y las causas que lo originan resulta de gran importancia para quienes deben crear, mantener y actualizar cualquier tipo de aplicación.

La evolución del software es un fenómeno que puede estudiarse de manera sistemática ya que se trata de un fenómeno en el que en cierta medida es posible encontrar patrones de regularidad. Entre los estudios reportados sobre la evolución del software, tiene especial relevancia el trabajo que Lehman inició a finales de los años sesenta del siglo XX. Lehman estudió diferentes parámetros de programas que habían pasado por varias actualizaciones, tales como el tamaño del sistema, el número de módulos añadidos, eliminados o modificados, el coste económico, etc., identificando reglas que parecían gobernar el proceso de actualización del software. En 1980, Lehman definió como software de tipo E aquellos programas informáticos escritos para realizar una actividad en el mundo real (por ejemplo, un sistema operativo o un programa para gestionar las existencias de un almacén), quedando incluidos en esta definición la mayoría de los programas informáticos utilizados hasta la fecha. Entre 1974 y 1996

Lehman enumeró 8 leyes de evolución del software (conocidas como leyes de Lehman), las cuales han sido empleadas en numerosos trabajos académicos.

La obsolescencia tecnológica de los VRLEs dedicados a la enseñanza de MSE ha sido señalada como un factor que influye de forma decisiva en la motivación que los estudiantes sienten hacia el uso de estas herramientas educativas. Así, se ha observado que si un VRLE no se actualiza periódicamente (y, por tanto, se vuelve obsoleto), los estudiantes se sienten cada vez menos motivados para utilizarlo, disminuyendo así su eficacia a nivel formativo.

En este artículo se analiza la influencia del proceso de obsolescencia tecnológica de los VRLEs y se analiza su relación con las leyes de Lehman. En el estudio llevado a cabo se empleó un primer grupo de dos VRLEs destinados a la enseñanza de MSE, desarrollados en 2013 y 2014 respectivamente, y un segundo grupo de dos VRLEs con la misma finalidad didáctica que los anteriores pero desarrollados en 2017 y 2018. Los VRLEs del segundo grupo se crearon empleando herramientas de desarrollo más modernas que las utilizadas para desarrollar los del primer grupo. Los VRLEs fueron utilizados por un total de 135 estudiantes de asignaturas de MSE del grado de Ingeniería Mecánica de la Universidad Católica de Ávila (España) entre 2013 y 2018 (VRLEs del primer grupo) y entre 2017 y 2020 (VRLEs del segundo grupo). El uso de los VRLEs en el aula siguió este esquema:

- Impartición de clases magistrales abordando conceptos teóricos y prácticos.
- Uso individual del VRLE por parte de los estudiantes, siendo posible seguir utilizándolos en sus ordenadores personales después de la clase si así lo desean.
- Resolución de ejercicios en pequeños grupos de alumnos (dependiendo de la finalidad didáctica del VRLE).
- Cumplimentación de encuestas.
- Análisis posterior por parte de los profesores de los datos extraídos de las encuestas.

Las respuestas de las encuestas ponen en evidencia que el proceso de obsolescencia tecnológica ejerce una influencia negativa en los VRLEs. En particular, se observa que los valores de motivación disminuyen con el tiempo hasta que se actualizan los VRLEs. Este hecho está relacionado con lo que establece la séptima ley de Lehman: "Los programas de tipo E serán percibidos como de calidad decreciente a menos que se mantengan rigurosamente y se adapten a un entorno operativo cambiante". Es decir, un programa que inicialmente ha sido bien percibido por los usuarios puede ser valorado negativamente por esos mismos usuarios transcurrido cierto tiempo. Este fenómeno se debe a que los criterios de aceptación y satisfacción de los usuarios suelen cambiar con el paso del tiempo. Una tendencia similar se observa en la interactividad, lo cual se relaciona con la séptima ley de Lehman, por un lado, y con la primera, por el otro. En efecto, la primera ley de Lehman establece que "un programa de tipo E que se utiliza debe adaptarse continuamente, pues de lo contrario se vuelve progresivamente menos satisfactorio", es decir, cuando se pretende que un programa sea útil a lo largo de los años debe adaptarse a los requisitos establecidos por el entorno en el que se utiliza. Por ejemplo, se observa que en la última década un gran número de programas y páginas web para el público en general han incorporado funcionalidades relacionadas con las redes sociales en respuesta al auge de su uso. En el caso de los VRLEs aquí estudiados, es probable que los alumnos demanden un tipo de interacción similar al que encuentran en otras aplicaciones basadas en VR. Por otra parte, el análisis de las valoraciones a la facilidad de uso y utilidad de los VRLEs muestra que estas se mantienen en niveles similares a lo largo de todo el periodo analizado.

En conclusión, los resultados obtenidos en este estudio son consistentes con la primera y séptima leyes de Lehman, y permiten afirmar que la valoración que los alumnos tienen de un VRLE está estrechamente relacionada con los procesos de actualización a los que este es sometido. La obsolescencia tecnológica que sufren los VRLEs repercute negativamente en la motivación que generan en los alumnos y en el nivel de interactividad que perciben, lo que hace que la herramienta educativa pierda parte de su eficacia a nivel formativo con el paso del tiempo. Debido a ello, en este trabajo de investigación se pone de manifiesto la necesidad de actualizar periódicamente los VRLEs utilizando herramientas de desarrollo actuales para asegurar que mantengan su eficacia formativa a lo largo de los años.

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The Technological Obsolescence of Virtual Reality Learning Environments

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Featured Application: The process of technological obsolescence suffered by the virtual reality learning environments used in higher education and its consequences in educational fields are analyzed in this paper.

Abstract: The concept of technological obsolescence that affects computer programs is a readily observable phenomenon that has been widely studied over the past half century. The so-called virtual reality learning environments (VRLEs) which are used to support university classes are significantly affected by this technological obsolescence, decreasing their formative effectiveness as the obsolescence process advances. In this study, the technological obsolescence of two VRLEs is analyzed by means of an empirical research based on survey results (N = 135) after using the VRLEs in engineering classes. Several key performance indicators (KPIs) were analyzed during seven academic courses, including motivation, interactivity, ease of use and usefulness. Since both VRLEs were updated during this research work, the influence of these improvements is discussed in detail from a technological obsolescence point of view. Results suggest that the technological obsolescence negatively affects the students' opinion regarding motivation and interactivity, but the other KPIs (ease of use and usefulness) are hardly affected. In contrast, results indicate that the technological obsolescence can be reversed if periodic updates of educational tools are carried out using modern development software.

Keywords: virtual laboratory; virtual reality learning environment; software evolution; software obsolescence; materials science and engineering

1. Introduction

Technological obsolescence affects any device that uses some kind of computer program since any software is constantly updated. Just look at the continuous updates that developers carry out on well-known computer programs or changes that web pages undergo over the years. An example of software evolution is the MS-DOS operating system, which based its operation on the introduction of written commands and was later replaced by Windows, whose operation is based on user interaction with graphic elements which the user must manually click. Another clear example can be seen if one visits a website developed for a large company in the late nineties and compares it with a more recently developed website for that same company: a modern website of this type has an aesthetic adapted to current preferences, links to social networks (nonexistent in the nineties), modern security protocols, etc. Similarly, today almost all the websites of universities and scientific journals are generally updated in a period not exceeding 5 years. This evolution of software is applicable to many other areas such as video games, operating systems and smartphone applications, user interfaces, and so on.

As noted by Lehman and Ramil [1], the transformation in the use of hardware (i.e. computers, smartphones, etc.) means that the domain of use and its applications change. For instance, a mobile telephone in the nineties was mainly used to make phone calls, while a current smartphone is commonly used for multiple tasks. In response to these changes, software must be able to keep up with the pace set by the social needs through the expansion and refinement of functionalities, the correction of failures and the improvement of performance [1], among others.

The importance of the software evolution process is reflected in the vast amount of money that development companies apply to evolve their programs after the first version has been launched [2]. As reported by Neamtiu et al. [2], the costs of maintenance and evolution of a software program can amount to several times the cost of developing the first version [3]. Knowing the evolutionary process of software and the causes that originate it is in fact of great importance for those who must create, maintain and update any type of application. As Lehman and Ramil [1] indicate, software evolution is a phenomenon that can be systematically studied since to some extent it is a phenomenon in which regularity patterns can be found. Software, in any of its many forms, is present in many aspects of today's life worldwide and thereby a massive number of programs are constantly being updated. Given the magnitude of any activity related to software maintenance and updating, it is not surprising that there is great interest in knowing this matter in depth. Indeed, there are numerous studies that investigate, among others: (i) the way in which software evolves [4,5]; (ii) the development of methods to help carry out the evolution of a certain software [6]; and (iii) the techniques to monitor such evolution [7,8].

Among all the reported studies concerning the evolution of software, the work that Lehman started in the late sixties has a special relevance. Lehman studied different program parameters that had gone through various updates, such as system size, number of modules added, deleted or modified, economic cost, etc. identifying rules that seemed to govern the software update process [9]. In 1980, Lehman defined as E-type software those computer programs written to carry out an activity in the real world (e.g. an operating system or a program to manage the stock of a warehouse [10]), being included in this definition most of the computer programs used to date. While Lehman listed the first 3 laws of software evolution in 1974 [9], it was not until 1996 when he extended this list to 8 laws [11]. Lehman's laws have been used in numerous works focused on the evolution of software, either to study them [12–16] or to use them as support for other studies [17–21].

As technology evolves steadily the use of virtual reality learning environments (VRLEs) has rapidly emerged as a promising technology that provides opportunities for flexible, adaptable, interactive and personalized learning experiences. If teaching methods are approached from a constructivism viewpoint, students shall play an active role in their own learning process [22], not merely being passive receivers of information [23]. The basic idea of constructivism is that problem solving is at the heart of learning, thinking, and development. As students solve problems and discover consequences of their decisions, they can build their own understanding and gain effective skills to solve real problems [22]. The premise is that students only deeply understand what they have constructed. Consequently, the student interaction with the environment (real or virtual) [23] is necessary. Thus, virtual reality (VR) is an effective support in the application of the constructivist strategy [24]. The use of VRLEs and VR in higher education and industry using varied computing infrastructures provide viable means to stimulate innovation, teamwork and cost-effective options while providing quality education and training. This is understandable if one considers that the emergence of these educational tools (which, in turn, is the result of technological evolution) has allowed students to interact with virtual environments in a way that would have been impossible few decades ago. This fact has brought about the possibility of implementing new teaching concepts and methods from a constructivism point of view, where the student's interaction with the virtual environment plays a key role. Enabling the learning and teaching through VRLEs will help make students be more competitive, eager to learn new concepts, ready to work collaboratively with other people in different disciplines and expertise, adaptable in new job environments and innovative-driven to seek entrepreneurship opportunities. For this reason, VRLEs have been the subject of different studies that have indicated which characteristics are those that arouse greater motivation among students [25–31]. One of the main conclusions drawn from these studies indicates the technological obsolescence of VRLE as a factor that decisively influences the motivation that students have when using these educational tools. Thus, it has been observed that if a VRLE is not updated periodically (and therefore becomes obsolete), students increasingly feel less motivated to use it, hence decreasing its effectiveness at a formative level [32].

For this reason, in this article the authors analyze the influence of the technological obsolescence process of VRLEs in some of its key performance parameters (KPIs), such as motivation, interactivity (i.e., the way in which the user manipulates the VRLE, as well as the type and quality of actions that he/she can perform in the virtual environment), ease of use and usefulness. These specific KPIs have been chosen because they are the most representatives of the VRLEs according to previous studies [33–43]. In addition, the relationship between technological obsolescence of VRLEs and Lehman's laws is raised. The results obtained are based on a 7-year study (from the 2013–2014 academic year to the 2019–2020 course) using different VRLEs. The use of different VRLE designs–based on software from different years – and the comparison of results from surveys presented to 135 engineering students, have demonstrated the negative influence of the process of technological obsolescence on VRLEs. In this way, it has been verified that through a periodic update of VRLEs using current development tools it is possible to restore their KPIs to the levels before the obsolescence process began.

2. Virtual Reality Learning Environments

2.1. Development of the VRLEs

Learning ternary phases diagrams (TPD) and crystal lattices (CL) usually generate problems of spatial visualization in students reading topics in Materials Science and Engineering [36,44,45], since they must be able to mentally recreate in three dimensions complex structures and overlapping elements. To solve this problem, the authors of this article developed and used in classes two VRLEs that aim to improve the spatial understanding of TPD and CL, respectively. Some years later, these VRLEs were updated using development tools different than the ones used for the creation of the first versions, as described below, and applied again in the classroom. In order to differentiate between the two VRLEs previously developed from those developed later, the first ones are named "VRLEs-1" (first version of both VRLEs of TPD and CL), and the second type are named "VRLEs-2", describing the two VRLEs of TPD and CL developed afterward (Figure 1). The workflow followed during the lifecycle of all VRLEs has been the same in all cases (Figure 2), similarly to that used in previous studies such as those by Ren et al. [46] and Rubio et al. [47,48].

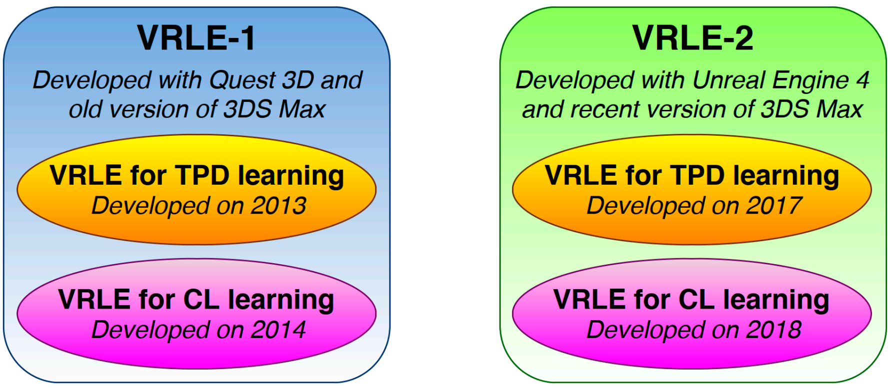


Figure 1. Classification of the VRLEs analyzed in this study: (i) former versions, VRLE-1 (left-hand side); and (ii) more recently developed versions, VRLE-2 (right-hand side).

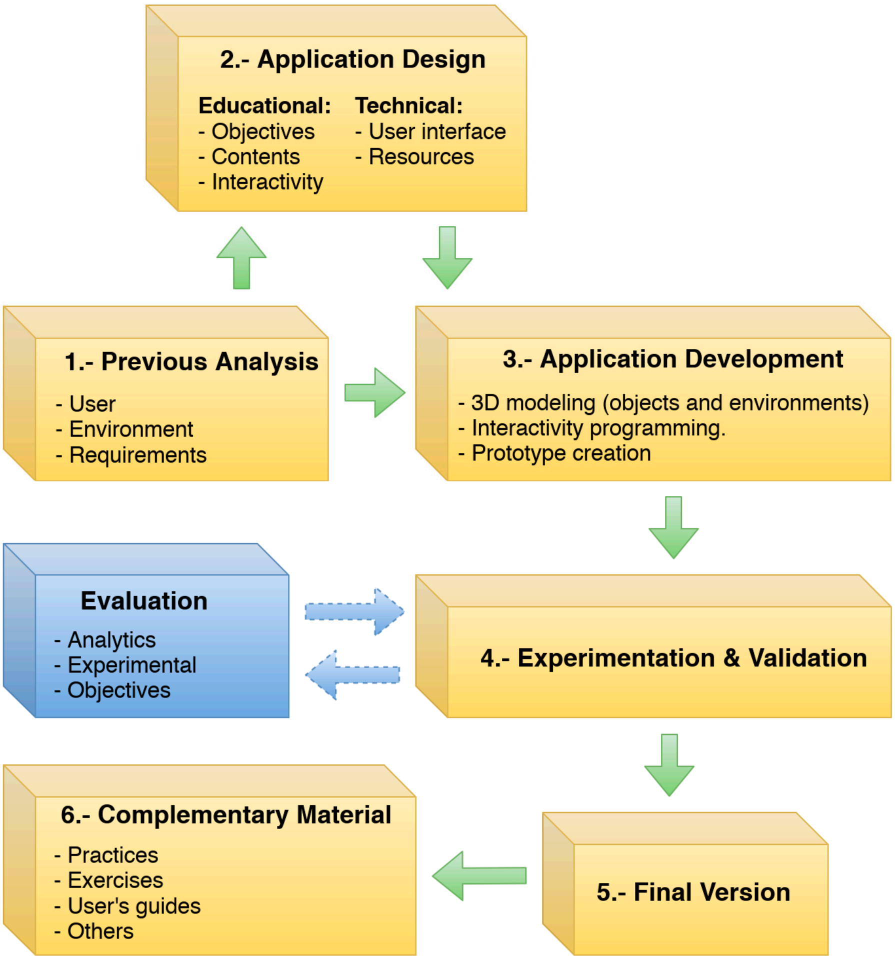


Figure 2. Workflow followed during the VRLEs lifecycle, based on previous works.

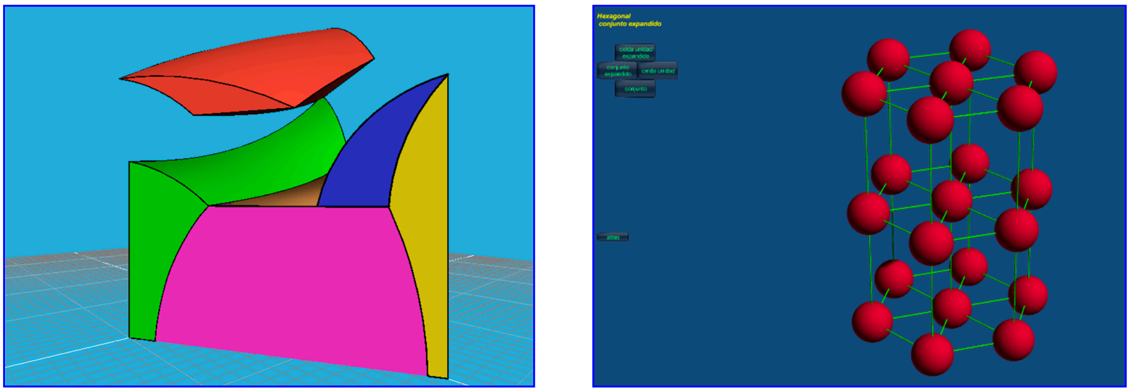
The development of each of the stages in Figure 2 was identical for each VRLE, with the exception of the third stage. During that stage (application development) the 3D modeling of the virtual environment, assignment of materials, lighting application to the scene and programming of VRLE interactivity are carried out. However, the programs used to develop VRLE-2 were either updated versions of those employed with VRLE-1 or were different programs altogether.

To create virtual environments (i.e., 3D modeling, application of materials and lighting) 3DS Max® (version 2013, Autodesk, San Rafael, CA, USA, 2012) was used in all cases, but a more recent version (version 2017, which was released on 2016) of this program was used to create the VRLE-2. This latest version of 3DS Max® allows the creation of virtual environments that are more realistic and aesthetically more attractive than those created with the older version because it offers a larger library of materials as well as more lighting options.

The interactivity of the VRLE-1 systems was programmed using Quest 3D® (version 5.0, Act-3D, Warmond, The Netherlands, 2012), while Unreal Engine 4® (UE4, version 4.13, Epic Games, Cary, NC, USA, 2016) was employed to program the VRLE-2 systems. Quest 3D® is a basic platform that allows the programming of three-dimensional environments with low levels of graphic realism and interactivity. On the contrary, UE4 is a game engine that is currently used to program a large number of video games. This game engine allows one to program complex environments with great graphic realism and high interactivity. UE4 also offers the possibility of subjecting virtual environments to physical laws, which allows simulating more realistic collisions or the effects of gravity, among others. Furthermore, UE4 uses a physics-based rendering system, which calculates the interaction of light with materials through physical equations [49]. In addition, programming on this platform is comparatively simpler with respect to others as it is based on a visual scripting system, thus eliminating the need to write complex computer codes [50].

2.2. Description of the VRLEs

The VRLE-1 systems (Figure 3) are non-immersive virtual reality (VR)-based applications which run generally on a personal computer, the user interaction is carried out using a keyboard and a mouse and the virtual environment is displayed via a monitor [26,36,44]. The VRLE-1 dedicated to the TPD understanding (Figure 3a) shows a three-dimensional illustration of an ideal TPD model where it can be distinguished different parts (each part corresponding to a specific phase, resulting from the combination of three different components at several ranges of temperature). A given user can manipulate, by means of a mouse, each part to understand the TPD model and its individual phases spatially. Thus, the user of this VRLE can perform on the virtual TPD model operations such as: separate and identify different individual phases, rotate elements or apply transparencies to the surfaces to visualize hidden areas, etc. These operations allow users to see –and hence better understand– invariant points (e.g. eutectic, peritectic, etc.) as well as to have an improved view of the relation between the concentration of the three components, temperature and phases formation. On another hand, the VRLE-1 dedicated to CL (Figure 3b) offers the possibility of exploring different types of crystalline networks such as those that are part of the elementary structure of metallic materials. To do this, the VRLE allows users to choose and explore one of the 14 Bravais lattices. Once a crystal lattice has been selected, the user can perform several operations on the cell (by means of the mouse) such as: do 3-axis free rotation, create section views (allowing user to clearly see atoms within the lattice, among others), expand unit cells, etc.



(**a**) (**b**)

Figure 3. Illustration of previously developed VRLEs-1: (**a**) VRLE-1 system dedicated to TPD calculations and (**b**) VRLE-1 system focused on CL approximations.

The development tools used to create the VRLE-1 systems do not allow to generate environments with high levels of graphic realism, so both TPD and CL results are displayed in empty spaces, using lighting and smooth and textured colors, an evidence of the technology of the time in which they were implemented. Moreover, the development tools used at that time (Quest 3D® and an older version of 3DS Max®) do not allow the VRLEs to deliver a high level of interactivity, so that the actions and visualization options offered to the user are rather limited.

The VRLE-2 systems (Figure 4) are non-immersive VR-based applications that also run on a personal computer, are controlled by a keyboard and a mouse, and are displayed on a monitor. These VRLEs allow users to explore the virtual environment in a similar way as he/she would do in a first-person shooter video game [51,52]. Since these later versions were developed with more modern tools, the VRLE-2 systems have a considerable improvement in both their visual appearance and interactivity. Hence, in the new version of the VRLE dedicated to TPD studies (Figure 4a), the user can move freely through a laboratory environment similar to that in any university, in which a hologram of a TPD can be placed in the middle of the room. In addition, this version of the VRLE offers more possibilities for interaction than in the previous versions (such as obtaining isothermal sections of a TPD virtually). Likewise, the new version of the VRLE dedicated to CL (Figure 4b) allows any user to move freely through a virtual museum whose exhibition halls show the 14 Bravais lattices [51].

(**a**) (**b**)

Figure 4. Screenshots of the VRLEs subsequently developed (VRLEs-2): (**a**) VRLE-2 system dedicated to TPD studies and (**b**) VRLE-2 system designed for CL investigations.

As the user approaches any of these lattices, the VRLE offers more possibilities for exploration and interaction than in the case of the previous version (Figure 3b), for instance revealing the unit cell and the expanded set with its geometric parameters, directions and crystallographic planes, octahedral and tetrahedral gaps, coordination indices, sections and families of planes and directions, etc. A complementary video is available in the supplemental section of this paper, which better clarifies all the technical options offered by this last VRLE. Therefore, both VRLE-2 systems (Figure 4) offer a more realistic and attractive appearance and more interaction options than prior versions (VRLE-1 systems in Figure 3).

3. Application in the Classroom

The use of VRLEs, both the former versions (Figure 3) and the later ones (Figure 4), have followed the same overall procedure, which is illustrated in Figure 5 and is similar to that used in prior studies reported by Mirauda et al. [53]. This procedure has been implemented as an assignment regarding Materials Science and Technology, which is part of the program of the second course of Mechanical Engineering Degree at the Catholic University of Avila (Spain), between the academic courses 2013–2014 and 2019–2020, and consist of the following main stages:

- The instructor teaches master classes, during which he/she addresses among others, both the theory and solution of practical exercises concerning TPD or CL problems. This stage lasts approximately two weeks (8–10 class hours) for teaching binary and ternary phase diagrams, and one week (2–4 hours) to explain the concepts related to CL.
- The use of VRLE in the classroom under the supervision of the instructor (0.5–1 hour). In addition, the student can continue using the VRLE on his/her personal computer after class as needed.
- Solution of exercises related to CL in groups of 2–4 students (in the case of TPD there is no solution of exercises). The duration of the solution process of these exercises, plus the corresponding correction by the instructor, typically involves 2 hours in the classroom.
- Survey fulfillment by students. These surveys aim to evaluate specific KPIs of the VRLEs: motivation, degree of interactivity, ease of use and usefulness (Table 1).
- Analysis of the data obtained through the above surveys.

Table 1. Questions (related to this article) designed on surveys for students.

Question	Number	KPI
Rate from 1 to 10 the following features of the VRLE (1 the lowest rate and 10 the highest)	1	Motivation felt when using the VRLE
	2	Interactivity level of the VRLE
	3	Ease of use of the VRLE
	4	Usefulness of the didactic tool

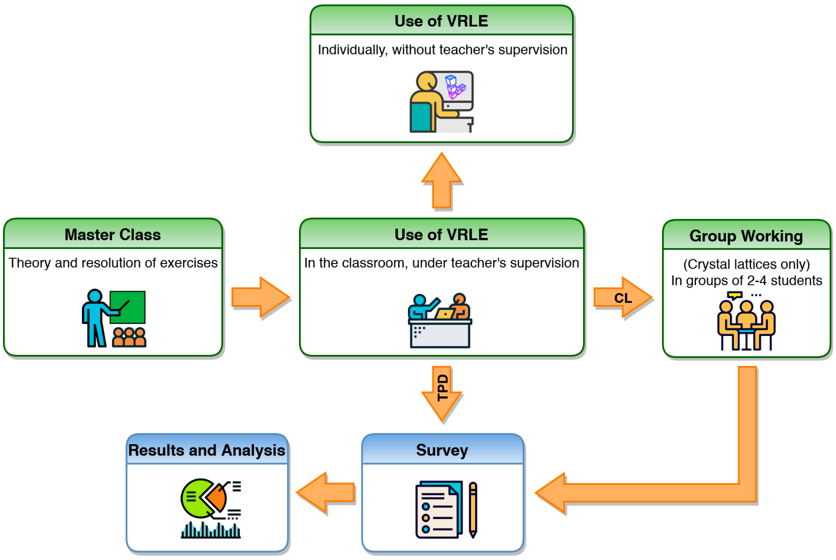


Figure 5. Procedure used to implement the VRLEs in the classroom.

The authors of this article have verified that solely applying the above stage corresponding to master classes (theory explanation and practical exercises solution) the teaching-learning process is incomplete, so that often students forget quickly what they have seen or heard in the classroom. Despite this, using VRLEs has demonstrated to improve the spatial understanding of students particularly in both TPD and CL exercises, so that they later assimilate related concepts. This certainly results in students achieving better meaningful learning and retaining concepts learned in class for longer periods of time [36].

4. Results

In total 135 students participated in the study between 2013 and 2020. From this set, 103 students used the older versions of the VRLEs (VRLEs-1, Figure 3), of which 82 used the VRLE-1 dedicated to the TPD exercises (Figure 3a) and 81 the VRLE-1 dedicated to CL studies (Figure 3b). The average scores assigned by the students to each question (Table 1) are summarized in Table 2. Furthermore, as shown in Table 3, 53 students used the later versions of the VRLEs (VRLEs-2), of which all of them used the VRLE-2 dedicated to solve TPD exercises (Figure 4a) but only 32 students used the VRLE-2 system (Figure 4b) dedicated for CL studies. The average scores assigned by the students to each question (Table 1) are shown in Table 3. The results of both Tables 2 and 3 are illustrated in Figure 6 (data corresponding to both VRLE versions of the TPD) and Figure 7 (data corresponding to both VRLE versions of the CL).

Table 2. Mean and standard deviation (σ) of students' scores from surveys given from 2013 to 2017 to each question of the Table 1 for VRLEs developed formerly (VRLE-1, Figure 3).

VRLE-1	Academic Year	Number of Students	Question 1		Question 2		Question 3		Question 4	
			Mean	σ	Mean	σ	Mean	σ	Mean	σ
TPD CL	2013–2014	22	8.6 - -	0.50 - -	7.5 - -	0.96 - -	7.1 - -	0.75 - -	9.7 - -	0.48 - -
TPD CL	2014–2015	20	8.5 7.5	0.61 0.61	7.2 9.0	0.89 0.85	7.2 9.0	0.83 0.74	9.7 9.7	0.47 0.59
TPD CL	2015–2016	20	8.1 7.5	0.72 0.69	6.5 8.5	0.89 0.76	7.0 8.8	0.73 0.75	9.7 9.6	0.49 0.60
TPD CL	2016–2017	20	7.5 7.3	0.87 0.73	6.2 8.2	0.77 0.82	7.1 9.1	0.79 0.65	9.7 9.8	0.47 0.44
TPD CL	2017–2018	21	- - 6.9	- - 1.00	- - 7.5	- - 1.03	- - 8.9	- - 0.76	- - 9.7	- - 0.46

Table 3. Mean and standard deviation (σ) of students' scores from surveys given from 2017 to 2020 to each question of the Table 1 for VRLEs developed later (VRLE-2, Figure 4).

VRLE-2	Academic Year	Number of Students	Question 1		Question 2		Question 3		Question 4	
			Mean	σ	Mean	σ	Mean	σ	Mean	σ
TPD CL	2017–2018	21	9.2 - -	0.75 - -	8.3 - -	0.60 - -	7.4 - -	0.80 - -	9.7 - -	0.46 - -
TPD CL	2018–2019	21	9.1 9.5	0.74 0.46	8.3 9.8	0.64 0.33	7.3 9.2	0.73 0.58	9.8 9.8	0.44 0.54
TPD CL	2019–2020	11	8.8 9.6	0.75 0.38	8.2 9.8	0.60 0.34	7.6 9.3	0.66 0.34	9.6 9.7	0.50 0.47

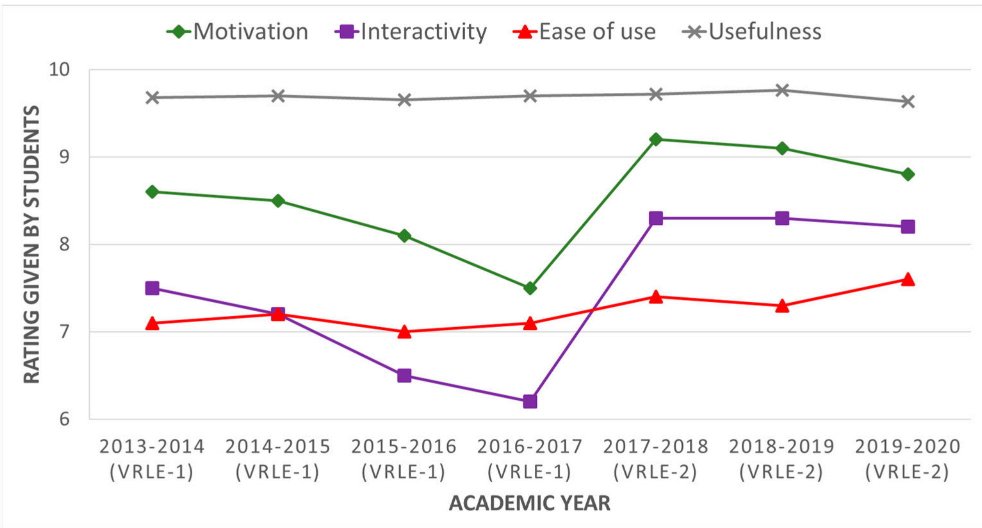


Figure 6. KPIs values of the VRLE of TPD over a period of academic years (former version, VRLE-1, and later version, VRLE-2).

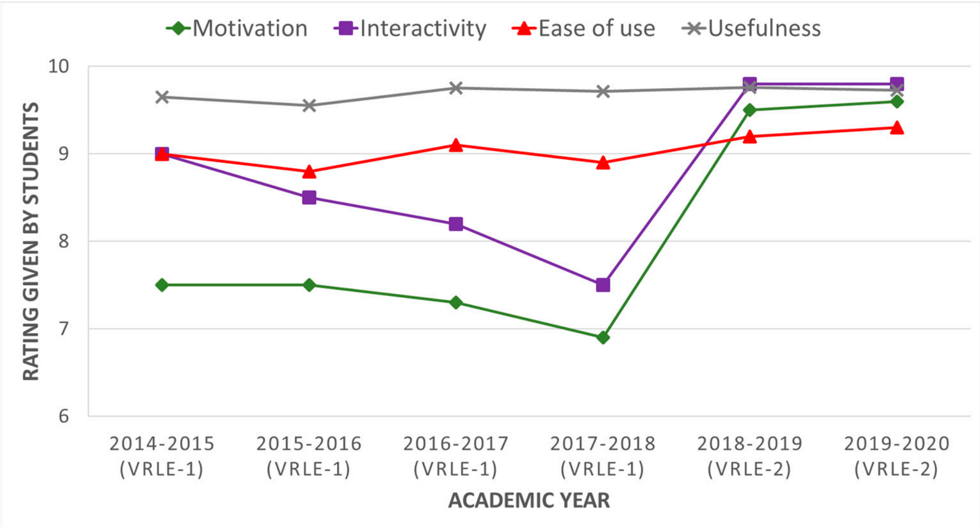


Figure 7. KPIs values of the VRLE of CL over another period of academic years (former version, VRLE-1, and later version, VRLE-2).

As can be seen in Figures 6 and 7, there are two similar evolutions: (i) the values of both motivation (question 1) and interactivity (question 2) decrease over time until the VRLE is updated (VRLE-2); (ii) the values of both ease of use (question 3) and utility (question 4) remain constant throughout the period of time evaluated. Looking at the VRLE-1 case, the KPI corresponding to motivation (question 1) has an average value of 8.6 (TPD) or 7.5 (CL) in the first academic year evaluated, decreasing this value year after year until reaching a value of 7.5 (TPD) and 6.9 (CL) in the last year of use. The interactivity KPI (question 2) is similar to the aforementioned, that is, at the beginning of the VRLE-1 usage, the interactivity KPI has an average value of 7.5 (TPD) and 9.0 (CL), which drops in each course until reaching a value of 6.2 (TPD) and 7.5 (CL) in the last course evaluated. By contrast, as seen in Table 2, this decreasing trend changes in both KPIs just at the moment when the period of use of VRLEs-2 begins. In particular, the motivation KPI reaches a value of 9.2 (TPD) and 9.5 (CL) at the beginning of the period of use of these new versions of VRLEs. Similarly, one can observe in the interactivity KPI of the VRLE that the values reach 8.3 (TPD) and 8.3 (CL) at the beginning of the use of the updated version (VRLE-2). Regarding standard deviation values, results shown in Table 2 indicate a low dispersion of the students' feedback (the maximum value is 1.03).

From Tables 2 and 3, as well as Figures 6 and 7, it is verified that the KPIs corresponding to the ease of use (question 3) and usefulness (question 4) have values that vary little throughout the period of time studied, regardless of the version of VRLE used. Thus, the ease of use KPI acquires values between 7.6–7.0 (TPD) and 9.3–8.9 (CL). In addition, the usefulness KPI acquires values ranging between 9.8–9.7 (TPD) and 9.8–9.6 (CL). In both of these KPIs the standard deviation is low, never exceeding 0.83, which indicates that there is little dispersion in the individual assessments taken from the surveys and, consequently, the opinion of the student body is quite homogeneous.

5. Discussion

From Figures 6 and 7 it can be seen that the motivation generated by the VRLEs-1 systems decreases as time goes by. It is also noticeable that from the moment the VRLEs-2 systems, which are the updated versions of the VRLEs-1 systems, began to be used the motivation of the students returned to high levels. This fact is related to what is stated in Lehman's seventh law, which read as follows: "E-type programs will be perceived as of declining quality unless rigorously maintained and adapted to a changing operational environment" [11] (p.3), i.e., a program that has been satisfactory for users during a certain period of time can be negatively valued by those same users. This phenomenon is due to the fact that the criteria of acceptance and satisfaction of the users often change with the passage of time, thus using feedback from the users to avoid the loss of quality of a program also acquires a great relevance [11].

Examining Figures 6 and 7, it is concluded that the assessment given by the students to the level of interactivity follows a trend similar to that observed in motivation, that is, it decreases continuously until the old VRLEs-1 are replaced by the newer VRLEs-2, at the moment when assessment given by the students to this parameter increases again. This fact could be related, on the one hand, to the seventh law of Lehman described above, and on the other hand with the first law of Lehman, which reads as follows: "An E-type program that is used must be continually adapted, else it becomes progressively less satisfactory" ([11], p.1). This law is easily understood from everyday experience: when a program that is intended to be useful over the years must be adapted to the requirements set by the environment in which it is used. For example, it is observed that in the last decade a large number of programs and web pages for the general public have incorporated functionalities related to social networks in response to the boom in their use (e.g. Twitter® or Facebook®). Regarding the case of the VRLEs studied here, it is likely that the students frequently demand the possibility of more interaction with any program that they already find in other similar VR-based applications.

Based on the two Lehman's laws set forth herein, and in accordance with the knowledge and experience of the authors in this article, the decrease in motivation and level of interactivity that students perceive throughout the years in which VRLEs-1 are used has its origin in the technological obsolescence to which they are exposed from the moment of their creation. When the first versions of VRLEs (VRLEs-1) were created with the development tools available at that time, they presented an aspect and handling similar to non-immersive VR-based applications that were available then. Consequently, students perceived VRLEs-1 as attractive and with highly interactive applications. However, over time the VRLEs-1 were at a disadvantage when compared to other similar applications. Therefore, students rated the VRLEs-1 worse and worse, as they perceived them to be outdated and with non-interactive applications.

When the VRLEs-2 were created, more modern development tools were used than those implemented to create the VRLEs-1, thereby achieving virtual environments with an aspect and a degree of interactivity matching the needed applications that could be found in that time. This means that the student body values again with high scores the aspects of motivation and level interactivity. As can be easily deduced, this is closely related to what is indicated in the seventh law by Lehman [11], which establishes that a constant work of adapting an application to the changing environment can make the perception of quality by users not decay over time. It can also be observed that Lehman's first law is fulfilled in the case of interactivity because by adding new possibilities for interaction in VRLEs-2, students have reacted positively in their assessments (Figures 5 and 6).

If the graphs of Figures 6 and 7 are analyzed in greater depth, it can be observed that the decreasing slope of the motivation and interactivity plots is more pronounced as time goes by. That is, in the following year the creation of the VRLEs-1 the scores provided by the students hardly vary, but over time the decrease in the overall score given by the students is more pronounced. These results suggest that VRLEs suffer speedy technological obsolescence since in just four years they can lose the level of motivation and interactivity they had at the time of their creation.

Lastly, it was observed that the assessment given by the students to the ease of use and usefulness of VRLEs hardly varies over the years or with the change in the VRLE version (i.e. with the passage of VRLE-1 to VRLE-2). In the authors' opinion, the invariability of such KPIs (ease of use and usefulness) is mainly due to two main factors: (i) the majority of students are used to using this type of virtual environment since they are very similar to video games and (ii) all the participating students in this study had used in the past, or were using at that time, other VRLEs in the classroom as tools that supported their master classes [26,27,33,35,37,38,52,54], hence students were familiar with their use as they had proven to be useful tools.

6. Conclusions

The results obtained in this study as we have seen are consistent with two of the laws enunciated by Lehman (in particular, with the first and the seventh law), which allow us to affirm that the assessment that students have of a VRLE is closely related with the degree of updates of the software used in its development. In other words, the technological obsolescence suffered by virtual educational platforms has a negative impact on the motivation they generate in students and the level of interactivity they perceive, which means that the educational tool loses part of its effectiveness at the formative level. This study has revealed that the use of current development tools allows the creation of educational tools that the students value positively in terms of motivation and interactivity. On the contrary, the assessment made by the students regarding both the ease of use and the usefulness of an educational platform does not seem to depend on the updating of the development tools used in its creation, but probably on other factors such as, for example, the fact the students are used to using similar modern computer applications.

Whenever an instructor develops an educational computer application in support of classes, he/she may not take into account that this type of program is subject to a rapid process of obsolescence nor of the negative consequences that this has on the efficiency of the teaching tool. Due to the great influence that the obsolescence process has on the formative effectiveness of VRLEs, this research paper highlights the need to update them periodically using current development tools. This way, instructors will ensure that their educational platforms maintain their formative effectiveness over the years.

Supplementary Materials: The following are available online at http://www.mdpi.com/2076-3417/10/3/915/s1, Video S1: The Technological Obsolescence of Virtual Reality Learning Environments.

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13. Conclusiones y Trabajo Futuro

En esta tesis doctoral han sido expuestos tres problemas relacionados con el uso de las RVT en el ámbito de la MSE. Cada uno de estos problemas ha sido abordado mediante el planteamiento de sendas hipótesis que han sido confirmadas mediante la consecución de objetivos concretos que han sido expuestos en detalle en cuatro publicaciones científicas en revistas indexadas por Journal Citation Reports [77–80].

El primer problema planteado se refiere a la dificultad que existe cuando se pretende conocer el estado del arte, es decir, cómo se han empleado las RVT en MSE hasta el momento. En este sentido, se ha confirmado la primera hipótesis planteada, es decir, que contar con uno o varios trabajos que sinteticen esta información facilitaría la adquisición de ideas que favorezcan el desarrollo de nuevas aplicaciones (o la actualización de las ya existentes) y la apertura de nuevas líneas de investigación. Esta hipótesis se ha confirmado alcanzando el primer objetivo establecido, es decir, se ha desarrollado un trabajo que analiza y cuantifica el uso de las RVT en la MSE, y se ha ampliado mediante otro trabajo que pone el foco en la enseñanza de cristalografía. En efecto, los trabajos “Reality-Virtuality Technologies in the Field of Materials Science and Engineering” [77] y “Virtual and Augmented Reality Environments to Learn the Fundamentals of Crystallography” [78] permiten obtener una imagen global del estado actual del uso de las RVT en la MSE. En ambas publicaciones se ha llevado a cabo una búsqueda sistemática que ha permitido describir de modo resumido numerosas aplicaciones basadas en el uso de RVT circunscritas al ámbito de la MSE. La síntesis realizada permite al lector acceder rápidamente a los conceptos principales que subyacen al funcionamiento de las aplicaciones descritas en multitud trabajos, lo cual redunda en un sencillo proceso de adquisición de ideas que le facilitan el desarrollo de sus propias aplicaciones. Por otra parte, el análisis cuantitativo llevado a cabo en “Reality-Virtuality Technologies in the Field of Materials Science and Engineering” [77] ha puesto de manifiesto diferentes aspectos que facilitan la apertura de nuevas líneas de investigación. Así pues, ha quedado descrito que la literatura científica apenas ha abordado el uso de RVT en áreas de MSE diferentes a “estructura de materiales, procesado y propiedades”, siendo por tanto posible abrir nuevas líneas de investigación en casi cualquier otro área de MSE. Por otra parte, ha quedado evidenciado que prácticamente la totalidad de las aplicaciones descritas en la literatura científica tienen como finalidad dar soporte a la docencia o a la investigación, lo cual puede ser debido a que los autores de estos trabajos desarrollan su actividad laboral en el seno de la universidad. Este hecho revela la oportunidad e interés de desarrollar nuevas líneas de trabajo en prácticamente cualquier sector diferente a la docencia o la investigación (como por ejemplo comercio, industria, transporte o construcción, entre otros), resultando conveniente contar con la participación de profesionales ajenos a la universidad. Por último, se ha comprobado que el uso de VR es mayoritario en comparación con el uso de AR, siendo aún el uso de MR testimonial. En relación con esto último, es posible abrir nuevas líneas de investigación basadas en aplicaciones que empleen MR, tecnología que permite superar las limitaciones de interactividad que actualmente tiene la AR en su forma más empleada (teléfonos inteligentes y tabletas).

El segundo problema planteado se refiere al insuficiente aprendizaje significativo que en muchas ocasiones alcanzan los estudiantes de MSE tras emplear VRLEs. En este sentido, se ha confirmado la segunda hipótesis planteada, es decir, que es posible mejorar el aprendizaje significativo actuando sobre el proceso de desarrollo de los VRLEs. Esta hipótesis se ha confirmado alcanzando el segundo objetivo establecido, es decir, de ha definido un nuevo proceso de desarrollo de VRLEs destinados a dar soporte a la enseñanza de MSE que permite mejorar el nivel de aprendizaje significativo que alcanzan los alumnos con respecto a VRLEs desarrollados anteriormente. En efecto, el desarrollo del trabajo "Meaningful Learning Through Virtual Reality Learning Environments: A Case Study in Materials Engineering" [79] ha permitido poner de relieve aspectos que deben ser tenidos en cuenta durante el desarrollo de los VRLEs con el fin de que estos permitan a los estudiantes alcanzar un adecuado nivel de aprendizaje significativo. Para llevar a cabo este estudio se analizó el proceso de desarrollo seguido durante la creación de diferentes VRLEs destinados a dar apoyo a la enseñanza de MSE (creados entre 2014 y 2018) los cuales fueron empleados en el aula por diferentes grupos de alumnos a lo largo de este periodo de tiempo, participando en total 103 estudiantes de asignaturas de MSE de la Universidad Católica de Ávila (España). Cada estudiante respondió, un año después de haber empleado cada VRLE, un cuestionario individual en el que se preguntaba acerca de conceptos aprendidos con ayuda de dicha herramienta didáctica. En primer lugar, los resultados obtenidos indican que el uso de herramientas de desarrollo actuales durante el proceso de creación de un VRLE favorece que los estudiantes sientan una alta motivación hacia su uso, lo cual facilita que se comprometan y se centren en su contenido. En segundo lugar, se ha determinado que el principal factor clave que determina que se alcance un elevado nivel de aprendizaje significativo es la implantación de un protocolo paso a paso que sirva para guiar al estudiante durante el experimento virtual. Así, durante el proceso de desarrollo de un VRLE debe determinarse el nivel de interactividad adecuado al objetivo docente que se persigue, es decir, el aprendizaje de un concepto o la realización de un experimento. En función de qué se pretende enseñar a través de un VRLE, se optará por un nivel de interactividad que irá desde un mundo abierto que permita llevar a cabo multitud de acciones hasta un sistema de guiado paso a paso que restrinja las acciones del usuario a las mínimas necesarias para alcanzar la finalidad didáctica perseguida.

El tercer problema planteado se refiere al hecho de que la valoración que dan los estudiantes de MSE a un VRLE decrece a medida que transcurren los años. En este sentido, se ha confirmado la tercera hipótesis planteada, es decir, que los VRLEs guardan relación con las leyes de Lehman y, en consecuencia, es posible evitar que la motivación de los alumnos hacia su uso decaiga con el paso del tiempo si se llevan a cabo trabajos de actualización periódicos. Esta hipótesis se ha confirmado alcanzando el tercer objetivo establecido, es decir, se ha evaluado en qué medida afecta el paso del tiempo a la valoración que tienen los estudiantes hacia los VRLEs destinados a la enseñanza de MSE, y se ha establecido que existe relación con algunas de las leyes de Lehman, tras lo cual se ha propuesto una metodología de actualización de VRLEs que logra que los estudiantes mantengan una percepción positiva de los mismos incluso con el transcurrir de los años. En efecto, el desarrollo del trabajo “The Technological Obsolescence of Virtual Reality Learning Environments” [80] ha puesto de manifiesto que los VRLEs empleados en la enseñanza de MSE son aplicaciones informáticas sujetas a las leyes de Lehman de evolución del software y, por lo tanto, someterlas a procesos periódicos de actualización permite que los estudiantes sientan una alta motivación hacia su uso a lo largo de los años. Para llevar a cabo este estudio se emplearon dos grupos de VRLEs (desarrollados en 2013 y 2014, y en 2017 y 2018, respectivamente), los cuales fueron empleados en el aula por un total de 135 estudiantes de asignaturas de MSE de la Universidad Católica de Ávila entre 2013 y 2020. Tras emplear estos VRLEs en el aula, los estudiantes respondieron cuestionarios cuyo análisis ulterior ha permitido poner de relieve que la valoración que hacen de un VRLE decae a medida que transcurren los años (debido al fenómeno de la obsolescencia tecnológica), pero tras una actualización empleando aplicaciones de desarrollo actuales esta valoración alcanza valores similares a las obtenidas al inicio de la vida útil del VRLE. Teniendo en cuenta que los VRLEs empleados en la enseñanza de MSE son programas de tipo E (según la definición dada por Lehman), los hechos observados en este estudio prueban que estas herramientas didácticas están sometidas a la primera y séptima leyes de Lehman. En consecuencia, ha sido posible concluir que existe la necesidad de actualizar periódicamente los VRLEs cuando se pretende sean empleados a lo largo de los años, utilizando para ello herramientas de desarrollo actuales para lograr así que los estudiantes sientan altos niveles de motivación hacia su uso y, de este modo, los VRLEs mantengan su eficacia a nivel formativo.

A raíz de las conclusiones extraídas en esta tesis doctoral se ha planteado desarrollar nuevas líneas de investigación enmarcadas en el uso de las RVT en el ámbito de la MSE. En primer lugar, se considera la posibilidad de investigar el uso de RVT en un ámbito diferente a la docencia o la investigación. En particular, se pretende estudiar el uso de AR o MR en el ámbito de la instalación de sistemas de tuberías de procesos sometidas a esfuerzos cíclicos, como ocurre en los compresores reciprocantes de determinadas instalaciones industriales (p.ej., refinerías). Con el fin de evitar la aparición de roturas en el material de las tuberías durante su funcionamiento, en la fase de diseño de este tipo de sistemas se llevan a cabo estudios de esfuerzo que tienen en cuenta las cargas y desplazamientos derivados de las pulsaciones generadas por el compresor. La hipótesis principal sobre la que giraría este trabajo es que una aplicación basada en AR o MR que emplee un preciso sistema LiDAR ayudaría a comparar in situ los desplazamientos reales de las tuberías con los teóricos empleados en su diseño. Si esta hipótesis fuese confirmada, sería posible conocer el grado de precisión de los estudios realizados durante el diseño del sistema de tuberías, así como detectar posibles anomalías de funcionamiento de instalación. En segundo lugar, se plantea abrir una línea de investigación centrada el guiado del usuario a través de los experimentos virtuales llevados a cabo en los VRLEs empleados en la enseñanza de MSE. En particular, se pretende estudiar en detalle qué factores resultan clave a la hora de diseñar un sistema de guiado paso a paso para que este se adapte completamente al objetivo didáctico perseguido. La hipótesis de partida sobre la que se iniciaría esta nueva investigación es que cada tipo de experimento virtual requiere un sistema de guiado paso a paso determinado, y mediante la adaptación de un conjunto de parámetros clave es posible desarrollar dicho sistema de guiado. Si esta hipótesis fuese confirmada, resultaría posible diseñar un sistema de guiado paso a paso óptimo simplemente conociendo el tipo de experimento virtual que se pretende enseñar y ajustando los parámetros clave del modo en que se hayan determinado durante la investigación.

14. Evidencias y Resultados

En este apartado se presenta el conjunto de indicadores de calidad de las revistas en que se han publicado los artículos que acreditan la investigación realizada, así como el conjunto de publicaciones en revistas científicas y congresos internacionales en los cuales se ha contribuido, reflejando el desarrollo y los resultados de las diferentes líneas de investigación que han culminado en esta tesis doctoral.

14.1. Indicadores de Calidad, Citas y Visitas

En este apartado se exponen, en primer lugar, los indicadores de calidad de las revistas en que se han publicado los artículos empleados para el compendio de esta tesis doctoral. Estos datos han sido extraídos de Journal Citation Reports [81] el 30 de octubre de 2022, y corresponden a 2021 por ser los más actuales disponibles en esta fecha. En segundo lugar, se muestra el número de citas y visitas de cada uno de los artículos que forman el compendio. Estos datos se han obtenido de MDPI [82] el 11 de noviembre de 2022.

14.1.1. Indicadores de Calidad de Applied Sciences

- Nombre completo de la revista: Applied Sciences-Basel
- Factor de impacto: 2.838
- Factor de impacto sin autocitas: 2.468
- Ranking por factor de impacto de la revista (JIF):
    - Química, Multidisciplinar:
        - Ranking JIF: 100/179
        - Cuartil JIF: Q3
        - Percentil JIF: 44.41
    - Ingeniería, Multidisciplinar:
        - Ranking JIF: 39/92
        - Cuartil JIF: Q2

        - Percentil JIF: 58.15
    - Ciencia de Materiales, Multidisciplinar:
        - Ranking JIF: 218/345
        - Cuartil JIF: Q3
        - Percentil JIF: 36.96
    - Física, Aplicado:
        - Ranking JIF: 76/161
        - Cuartil JIF: Q2
        - Percentil JIF: 53.11

14.1.2. Indicadores de Calidad de Crystals

- Nombre completo de la revista: Crystals
- Factor de impacto: 2.670
- Factor de impacto sin autocitas: 2.395
- Ranking por factor de impacto de la revista (JIF):
    - Cristalografía:
        - Ranking JIF: 12/26
        - Cuartil JIF: Q2
        - Percentil JIF: 55.77
    - Ciencia de Materiales, Multidisciplinar:
        - Ranking JIF: 227/345
        - Cuartil JIF: Q3
        - Percentil JIF: 34.35

14.1.3. Número de Citas y Visitas de los Artículos (a 11 de noviembre de 2022)

- Reality-Virtuality Technologies in the Field of Materials Science and Engineering [77]
    - Número de citas (Scopus / Web of Science / Google Scholar): 0 / 0 / 1
    - Número de visitas (resumen / texto completo): 568 / 547

- Virtual and Augmented Reality Environments to Learn the Fundamentals of Crystallography [78]
    - Número de citas (Scopus / Web of Science / Google Scholar): 16 / 15 / 28
    - Número de visitas (resumen / texto completo): 2111 / 2056
- Meaningful Learning Through Virtual Reality Learning Environments: A Case Study in Materials Engineering [79]
    - Número de citas (Scopus / Web of Science / Google Scholar): 24 / 17 / 45
    - Número de visitas (resumen / texto completo): 2919 / 2421
- The Technological Obsolescence of Virtual Reality Learning Environments [80]
    - Número de citas (Scopus / Google Scholar): 14 / 12 / 24
    - Número de visitas (resumen / texto completo): 6775 / 3174

14.2. Otras Publicaciones

A continuación, se listan otros trabajos académicos publicados en revistas y congresos internacionales a lo largo del desarrollo de esta tesis doctoral.

- Extremera, J.; Vergara, D.; Rubio, M.P.; Gómez, A.I. Design of Virtual Reality Learning Environments: Step-by-Step Guidance. In Proceedings of the 12th Annual International Conference of Education, Research and Innovation, ICERI 2019, Seville, Spain, 11–13 November 2019; International Academy of Technology, Education and Development: Valencia, Spain, 2019; pp. 1285–1290.
- Vergara, D.; Sánchez, M.; Garcinuño, A.; Rubio, M.P.; Extremera, J.; Gómez, A.I. Spatial Comprehension of Crystal Lattices through Virtual Reality Applications. In Proceedings of the 12th Annual International Conference of Education, Research and Innovation, ICERI 2019, Seville, Spain, 11–13 November 2019; International Academy of Technology, Education and Development: Valencia, Spain, 2019; pp. 1291–1295.

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