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

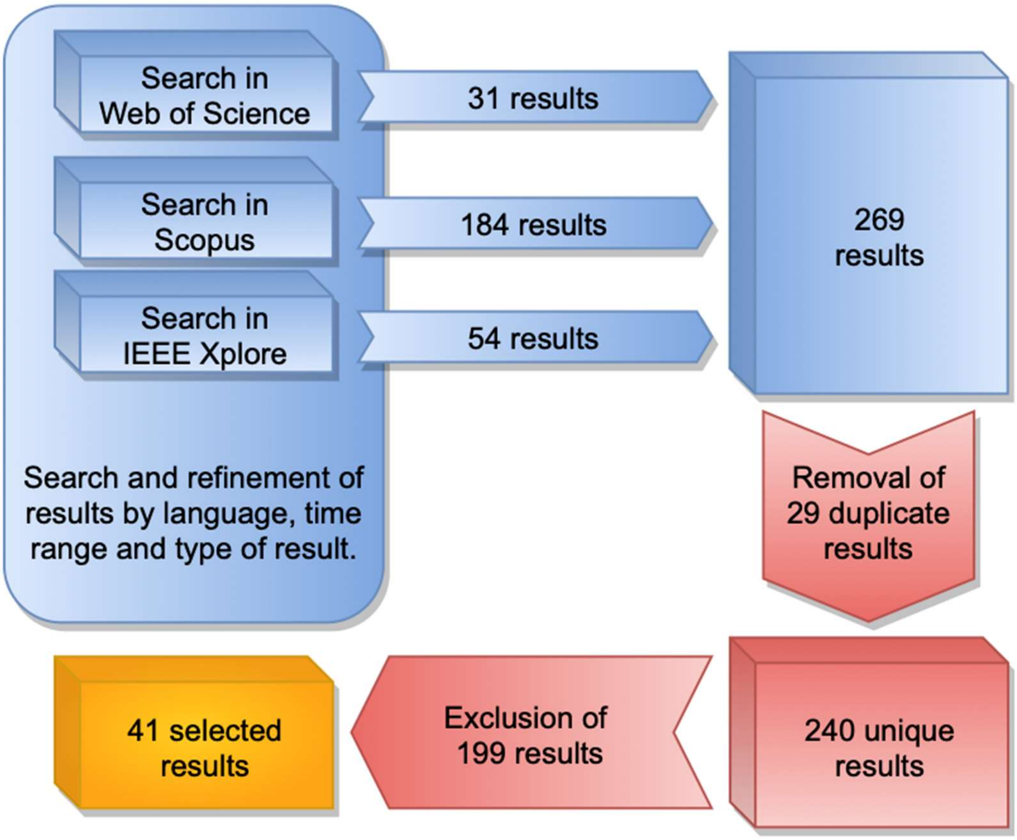

Figure 1. Illustrative diagram of the process followed for the selection of works.

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
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
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

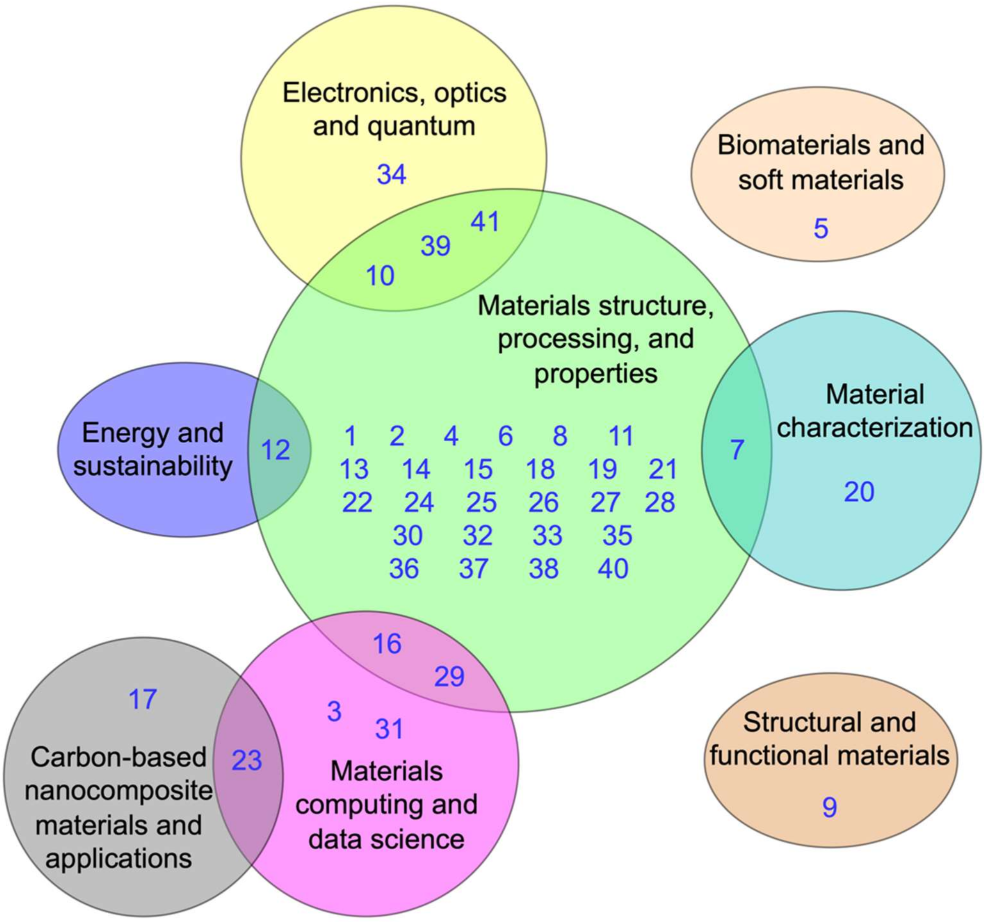

Figure 2. Area of MSE in which described applications are circumscribed. Numbers 1 to 41 identify the works listed in Table 4 (column "Work Number").

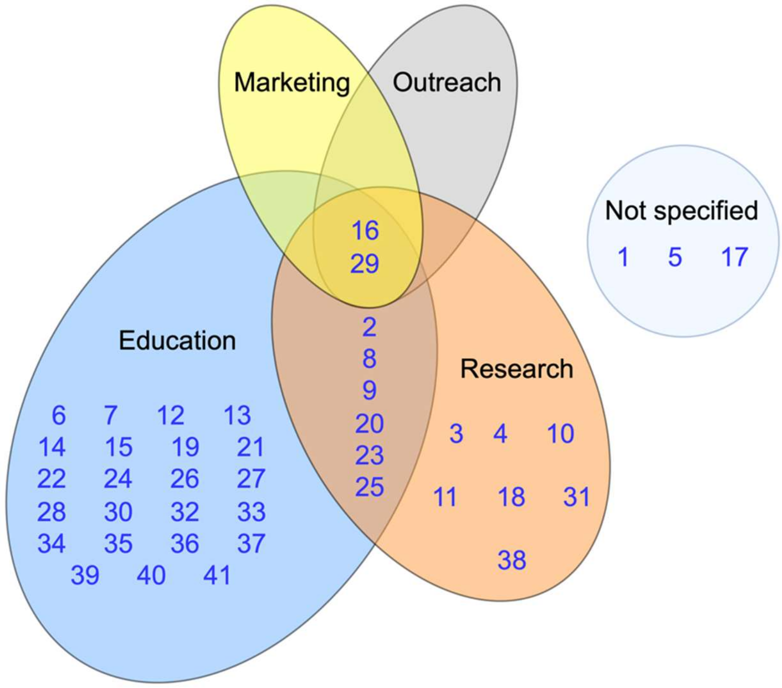

Figure 3. Target sector of the described applications. Numbers 1 to 41 identify the works listed in Table 4 (column "Work Number").

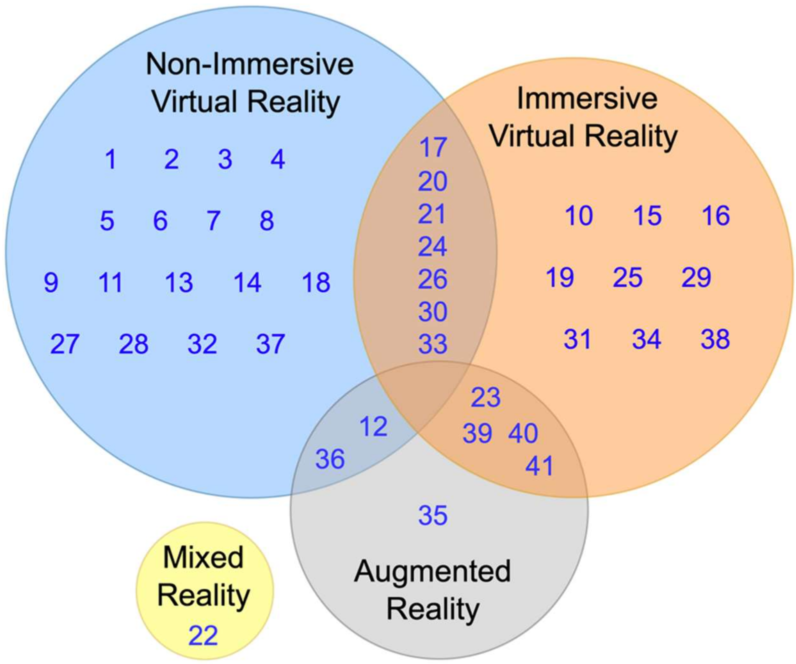

Figure 4. RVTs employed by the described applications. Numbers 1 to 41 identify the works listed in Table 4 (column "Work Number").

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.

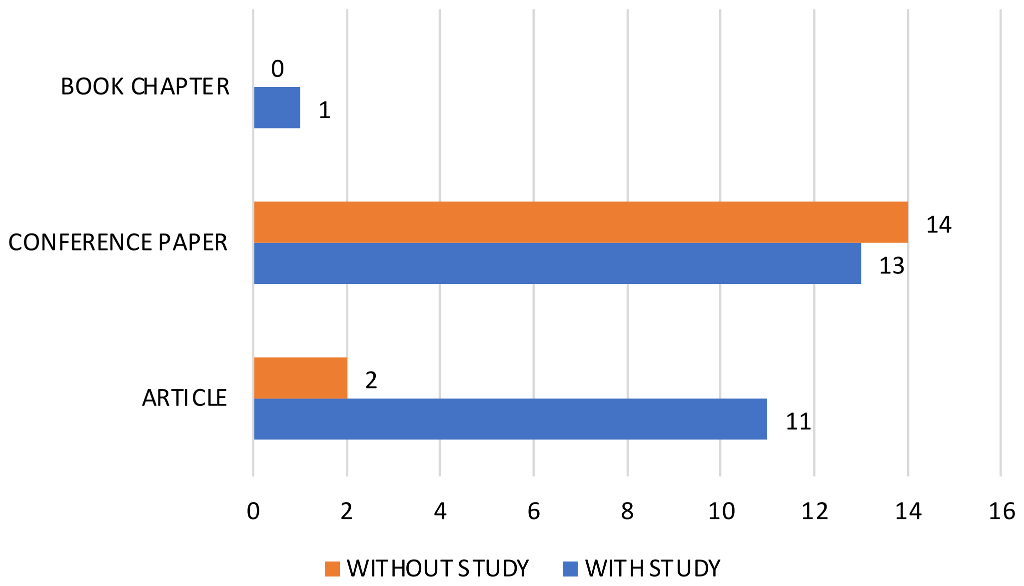

Figure 5. Type of documents analyzed, differentiating those that containing some type of empirical study from those that do not include any.

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%).

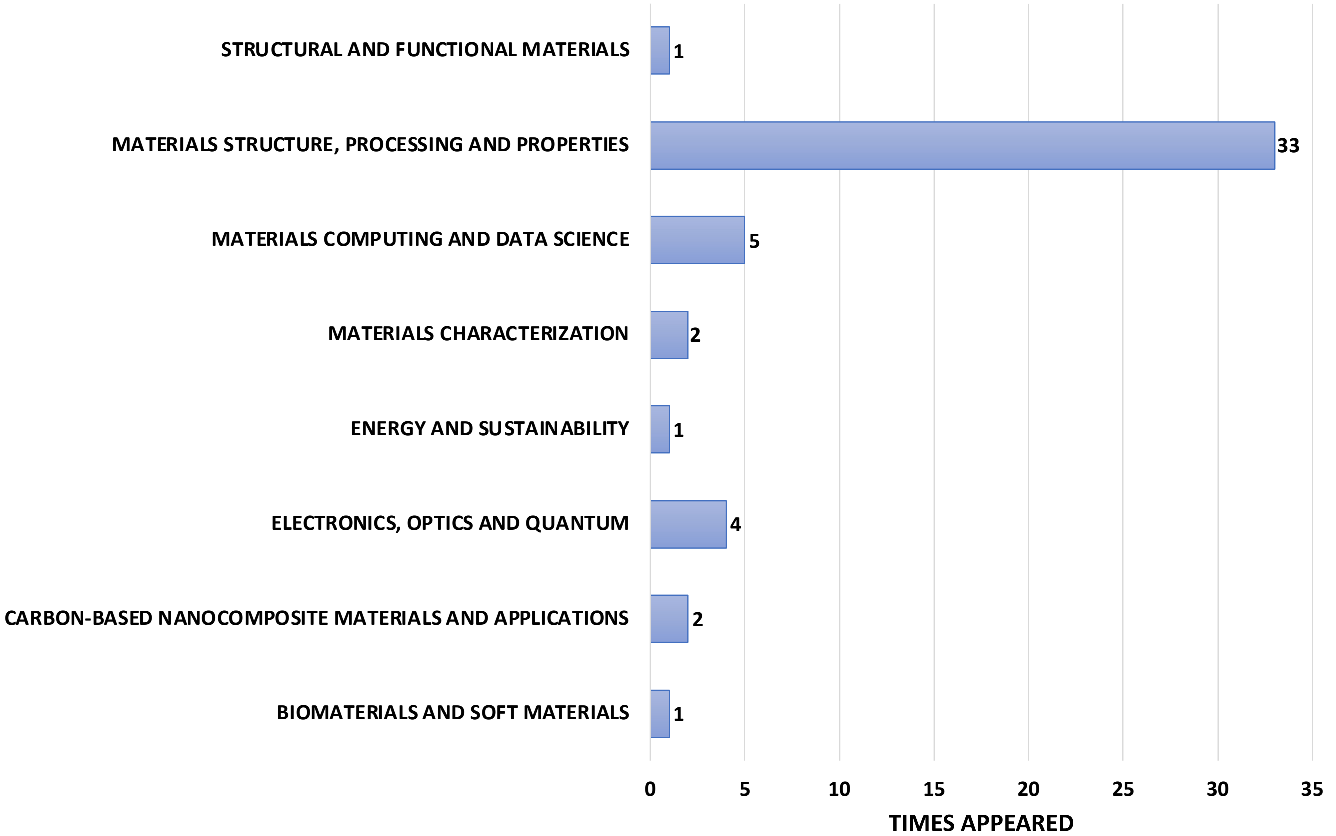

Figure 6. MSE area descriptive tags assigned to analyzed works and the number of times that these tags were used.

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.

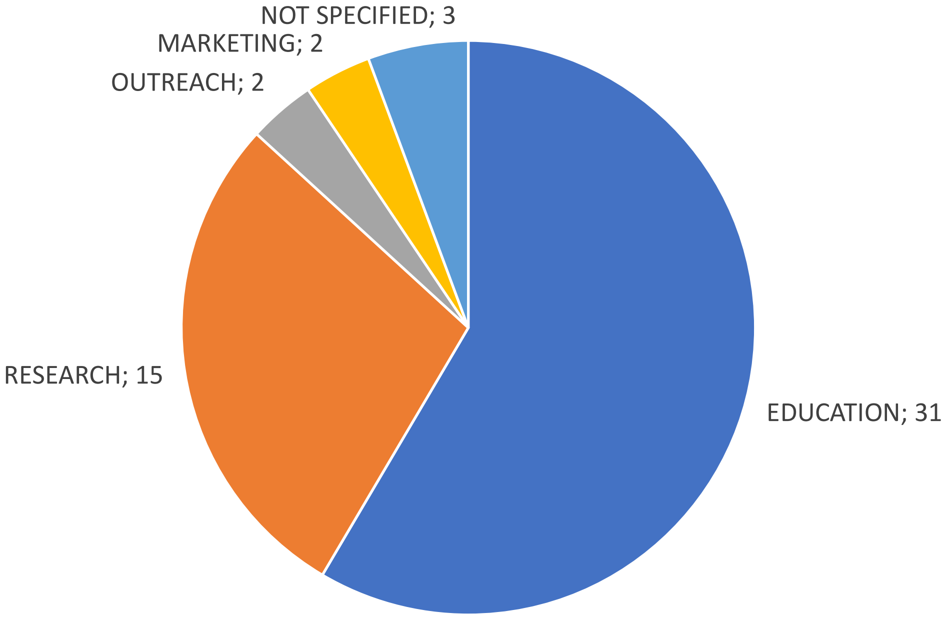

Figure 7. Number of times that the authors of the works analyzed declared directing the applications to education, research, outreach, and marketing.

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.

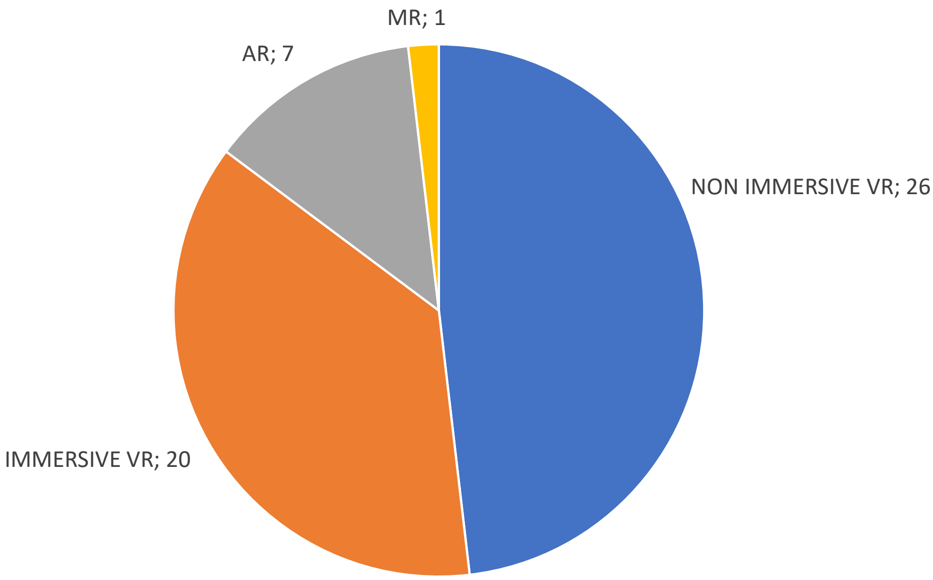

Figure 8. Number of times that immersive VR, non-immersive VR, AR, and MR technologies were used in the 41 works analyzed.

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.

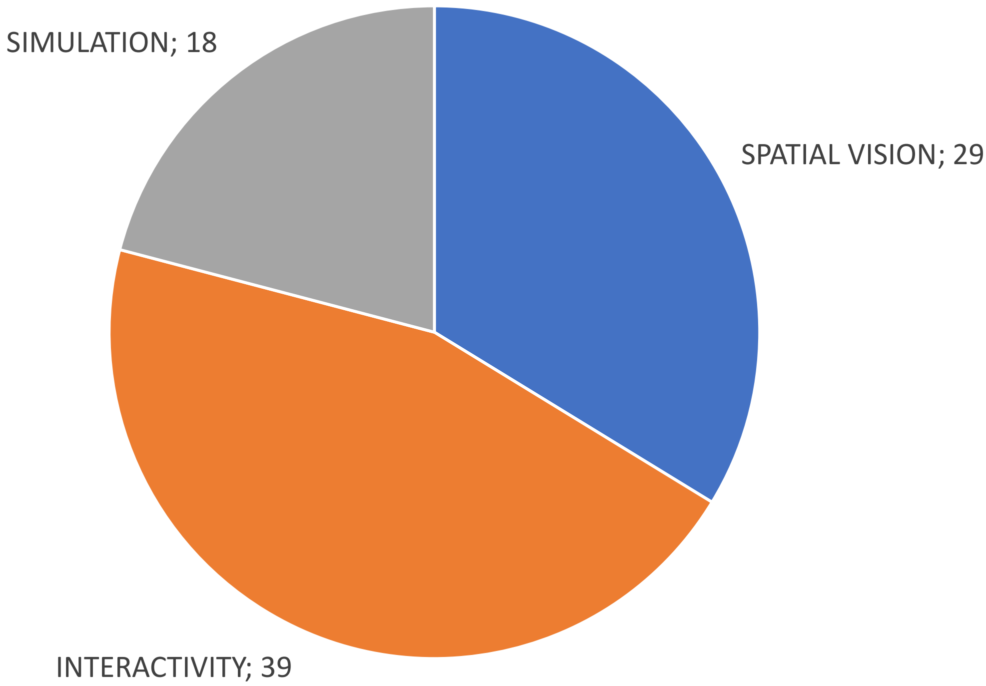

Figure 9. The number of times spatial vision, interactivity, and simulation were exploited in the works analyzed.

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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