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Mapping the Knowledge Base on Visual Reality Technology and the Manufacturing Industry

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Abstract

Virtual reality applications provide users with more than just realistic sight; they may also sense touch, hear, and even interact with virtual objects. With these significant advancements, virtual reality has seen recent growth surges in a number of sectors, including the manufacturing industry. It has to be successful in drawing attention from both academics and industry. It needs to be known how researchers are interested in the technology application. Therefore, examining the body of research on the connection between visual reality and the manufacturing industry is the goal of this research. The bibliometric study was carried out using the Scopus database. Using PRISMA, the sample procedure was finished. VOSviewer was utilized to search through 2,037 publications. This disclosed the expansion of the network, the most active contributing stakeholders, the backdrop of the intellectual framework, the research gap, and the greatest popular topic that needed to be filled. We observed that starting in 1992, papers pertaining to the influence of virtual reality on the manufacturing industry collected from the Scopus database were included. The words “augmented reality,” “virtual reality,” “process simulation,” “industrial internet of things,” “industry 4.0 technologies,” and “3D technologies" have been widely used since 1992. The density map's representation of contemporary themes includes “artificial intelligence” and “human-robot interaction.” The significance of the findings for researchers lies in their relevance to the past, present, and future, along with the identification of knowledge gaps.

Keywords: augmented reality, bibliometric, manufacturing industry, visual reality, VOSviewer.

1. Introduction

With the use of cutting-edge computer technology, virtual reality (VR) may simulate mechanics in a real or imagined world and provide users with a variety of intuitive feelings. [1] found that virtual reality (VR) has no one accepted definition; instead, definitions vary depending on the intended use and setup [2], [3]. Virtual reality (VR) may be thought of as a logical progression of conventional computer graphics to 3D displays with sophisticated inputs and outputs [4]. Its study is broken down into two categories: software and hardware [1], [5]. Early VR equipment was incredibly bulky, costly, and ineffective. After decades of development, VR systems as a whole can provide consumers with a higher degree of spatial immersion; technology has shrunk in size and become more affordable; and software has improved.

Virtual reality (VR) applications provide users with more than just realistic sight; they may also sense touch, hear, and even interact with virtual objects. With these significant advancements, virtual reality has seen recent growth surges in a number of sectors. It has been successful in drawing attention from both academics and industry. Researchers and practitioners are very interested in exploring the transformation of industries brought about by the fourth industrial revolution around the world [6]. The German government, academic institutions, and private businesses first introduced the idea of "industry 4.0," which seeks to leverage cutting-edge concepts and technology to move industrial manufacture into a new era known as "smart manufacturing" [7], [8]. Its goal is to incorporate cutting-edge technologies to raise manufacturing industry standards for efficacy, productivity, and quality [9]. Virtual reality (VR) is regarded as one of Industry 4.0's cutting-edge front-end technologies for enabling smart working [8]. The same is true for manufacturing.

According to [10], the five categories of VR technologies are olfactory/taste, haptic, visual, bio-signals, and auditory. Therefore, visual is further divided into augmented reality, immersion-typed, and desktop-typed [11]. In addition to prototypes, authoring technology includes the use of “computer-aided design,” “virtual reality modelling language,” and equivalents [10], [12]. In this research, AR and VR will have a nearly closer meaning because the search query considered them synonyms for virtual environments.

The manufacturing sector has seen substantial transformations ever since the onset of the initial technological revolution, introducing steam power and mechanized production [13]. Electricity and assembly lines were introduced into industries during the second technological revolution. The emergence of automation in the 1970s sparked a third technological revolution in industries [14]. “Smart production” [15] is made possible by the integration of digital technology into the manufacturing setting through initiatives like Industry 4.0 [16]. The realization of smart capabilities in the future manufacturing industry relies significantly on digital technologies. Digital twins [17], augmented reality (AR) [13], cloud computing [18], IoT [19], predictive maintenance [20], big data [21], and virtual reality [10] are a few examples of digital technologies.

The use of digital technologies has led to previously unheard-of amounts of data collection and information generation. Building cyber-physical production systems that seamlessly integrate the digital and physical worlds is the goal of Industry 4.0 [22]. By doing so, manufacturing will become more intelligent and consequently more flexible, adaptable, and autonomous [23]. Humans continue to be crucial to manufacturing processes, even with this emphasis on technology [24], [25]. AR is used to enable real-time, contextual human access to massive amounts of data produced by CPPS [22]. Because AR supports people in an intelligent manufacturing environment, enabling this Industry 4.0 manufacturing approach with a focus on human-centricity is crucial [26].

According to [27], the European Union has identified augmented reality (AR) as a key technology that will propel the growth of smart manufacturing. Researchers concentrate on augmented reality (AR) to accomplish the goal of facilitating human-digital data-based production system collaboration and interaction [14]. Although many technologies contribute to the fourth industrial revolution [27], augmented reality (AR) is the only one that focuses on enhancing human-machine and, consequently, human-intelligent manufacturing system interaction. Thus, it is essential to comprehend the present state of augmented reality in industrial research. In this instance, the bibliometric examination is required in order to determine the areas of structure, growth, and present knowledge based on the connection between virtual reality and the manufacturing industry that require more investigation or evaluation.

[28] assert that bibliometric analysis serves as an effective method for gauging the impact of publications within the scientific community. This approach is characterized as a statistical assessment of published book chapters, scientific articles, or books. Identifying key authors, core research, and their interconnections necessitates a systematic computer-assisted review process that surveys all publications within a specific topic or field [29], [30].

Bibliometric analyses have the capability to statistically portray official intellectual frameworks, revealing collaboratives, nations, co-citation patterns, sources, and citations, as well as keywords and correlations among fields of study. This is particularly evident when combined with social network analysis techniques, showcasing clusters and networks. Consequently, conducting a thorough analysis of the research trajectory contributes to a more profound comprehension of the subject.

[31]'s paper was about the role of virtual reality on manufacturing industry limited to only industry 4.0. This bibliometric manuscript studies the connection between virtual reality and the manufacturing industry as a whole, and not only 4.0; this leads to a wider scope compared to [31]'s research. Furthermore, the article used the Web of Sciences database, so since this study uses the Scopus database, it might be regarded as widening and supplementing the literature.

[32] used mostly content analysis to study the topic and a little bibliometric method, the result of which differs from that of bibliometric analysis. For instance, using correlation to look for a gap is quite different from the gap given by the keywords, and the same is true for the redundant topics. Furthermore, the authors did the study in 2015 which is due to time variant and speed of technological change, there might be a difference in coverage. These are the differences between the two.

Apart from the above gaps, this study was to correct the limitations reported by [33]: "the use of two databases for publication selection (Scopus, Web of Science)." This study uses only Scopus for data sampling and collection. Also, [33] was done for the period 2012–2022, which is too narrow as the domain started publishing in 1990s. To fill this gap, we did this study.

Therefore, the study's methodology for concentrating on the connection between virtual reality and manufacturing industry trends is still unknown. It is also uncertain who the main writers and contributors are in the most well-known publications on the connection between virtual reality and the manufacturing industry, as well as the research that is quoted the most. The objectives of this bibliometric review are to enhance scholars' comprehension of historical, current, and prospective trends and to propose potential avenues for future studies. Consequently, an assessment of the connection between virtual reality and manufacturing industry research was conducted using that science mapping methodology, concentrating primarily on these study questions:

RQ1: What is the trend in the growth of research on the connection between virtual reality and the manufacturing industry?

RQ2: Which countries, writers, sources, and publications have contributed the most to the understanding of the connection between virtual reality and the manufacturing industry?

RQ3: What is the scope of the knowledge framework for the literature on the connection between virtual reality and the manufacturing industry?

RQ4: In the connection between virtual reality and manufacturing industry research, what are the research gaps?

The goal of this research review is to use bibliometric analysis, the most effective way for analyzing the conceptual structure of the field, to develop a sustainable knowledge base by examining the corpus of research on the connection between virtual reality and the manufacturing industry [34]. Using bibliometric approaches, the study examined a dataset of 2,037 publications that were indexed by Scopus. Using descriptive statistics, trends in the composition and growth of the connection between virtual reality and manufacturing industry literature were recorded. Citations, co-authorship, co-citation, and co-occurrence analysis were used to find authorship, documents, and subject patterns [35].

2. Methodology

Using techniques for example co-occurrence analysis, citation analysis, co-authorship analysis, and co-citation analysis, the study performed a bibliometric analysis of the association between virtual reality and manufacturing industry literature [36]. “Several software tools are commonly used for bibliometric analysis. Some of the most prominent ones include VOSviewer, Bibliometrix (an R package), CiteSpace, and BibExcel, among others.” The literature uses the VOSviewer package to do bibliometric analysis [36]. The versatility of the VOSviewer software is the reason to use it. Contrary to most applications, VOSviewer provides a sizable graphical illustration of bibliometric networks [37]. First, on December 22, 2023, we looked over the literature on the connection between virtual reality and the manufacturing industry to obtain an up-to-date overview of the field and compile a list of frequently used terms. We established our inclusion criteria following the PRISMA procedure before commencing the data gathering process [38], [39].

2.1. Locating Resources for the Review

Given that empirical investigations have demonstrated Scopus to provide more extensive coverage of sources in the field of social sciences compared to the Web of Science, we opted to use the Scopus index as the data source for extracting papers [40]. According to [41], there is a possibility to argue that, acknowledging that the narrower coverage of Web of Science results in a database with higher-quality sources, it is important to note that this observation is subject to confirmation through objective verification, particularly in the context of specific topics. As a result, we looked to a prior study by [42] and found that there was a significant correlation between the citations and papers in Scopus and Web of Science.

2.2. Search Delimiting Criteria

Using the anticipated search string, we conducted our first search on December 22, 2023, on the "Scopus" database. We defined a set of inclusion and exclusion variables to limit our findings. After going through the four stages, we were able to extract the pertinent articles for our evaluation from the initial 4,776 articles that we found (Fig. 1). We were left with 4,373 articles after applying the topic area delimitation criteria, which included only papers from the computer science, management, engineering, business, accounting, econometrics, economics, finance, and social sciences domains. To obtain articles with just pertinent terms for the connection between virtual reality and the manufacturing industry, we employed keywords as inclusion and exclusion criteria. After removing 2,281 articles, 2,092 articles were left. We eliminated 55 papers written in other languages because we only required English-language publications. This left us with 2,037 final articles for our evaluation and bibliographic analysis.

In this instance, we entered the request in the Scopus Database by means of the "TITLE-ABS-KEY" tool [36]. We gathered all the material that was subjected to a peer review process by limiting the search to English-language publications in the "final papers" category that were released no later than December 22, 2023.

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach helped as the search criteria for the documents [39]. A Scopus article title, abstract, and keyword search were conducted using the following search terms: (“simulated reality” OR “augmented reality” OR “virtual reality” OR “artificial reality”) AND (“manufacturing industry” OR “manufacturing sector” OR “industrial sector"), and 4,776 documents were located during this search. 2,739 papers were eliminated following screening and eligibility verification because they had undesired specifications or were not sufficiently significant (refer to Fig. 1). In the finished database, 2,037 documents were included.

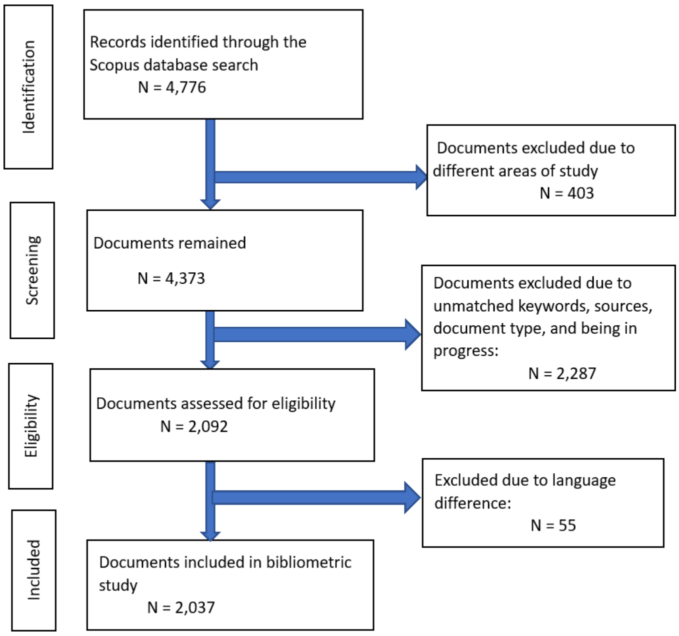

Fig. 1. The PRISMA Flow chart Showing Systematic Sampling [38]

3. Results and Discussion

2,037 documents, including citations, affiliations, authors, and titles, were stored for future analysis. Examples of advanced bibliometric analyses include co-citation and citation analysis, along with the "visualization of similarities" through co-citation and co-occurrence analysis. [36], [43]. Tableau, the VOSviewer package, and Excel were among the Scopus analysis tools used in this research [43]. This section unveils the results derived from the bibliometric examination of the literature on virtual reality. The responses to the research questions are presented in the following sequence:

3.1. Descriptive Trends in the Virtual Reality Knowledge Base

An essay written by Theasby P. J. published in 1992 titled “Virtues of Virtual Reality” served as the review's initial source. It wasn't until the year 1995 that scholarly interest really took off, as the number of papers increased annually. To further analyse the growth of the keywords, the timeframe was to be grouped into smaller time intervals. The study examined the temporal evolution of keywords by considering their timelines and normalising the frequencies by number of keywords in each time sub-period, as documented as per [44]. The evolution of keywords is illustrated for the entire period and each of the three sub-periods in Table 1. Regarding the initial phase, sub-period one (1992–2017) saw the publication of an average of just 17 publications annually (Fig. 2). The four terms that showed the largest co-occurrence, with more than 5 percent of the overall occurrences, were virtual reality, process simulation, augmented reality, and manufacturing industries.

Referred to as the "take-off phase," the second sub-period, which runs from 2018 to 2020, was marked by a progressive increase in the quantity of articles. Every year, on average, over 188 papers were published. The seven most common terms throughout the sub-period were “Industry 4.0 technologies,” “virtual reality,” “augmented reality,” “manufacturing industries,” “industrial internet of things,” “process simulation,” and “smart manufacturing systems”; each accounted for more than 5 percent of all terms used. The evolution of the industrial internet of things, smart manufacturing systems, digital twins, cross-reality, smart technologies, and assembly assistance systems took place throughout this period. However, the keywords “cross reality,” “smart technologies,” and “assembly assistance systems” lasted for only this single period and disappeared. The use of specific co-words like “virtual reality” and “augmented reality” might be the reasons for the disappearance of cross-reality. During this period, the keyword “industrial internet of things” became more and more popular among scholars as the foundation for virtual environments.

Table 1 Keywords’ growth movement in the connection between virtual reality and manufacturing industry

d	1992-2023			1992-2017			2018-2020			2021-2023		
	Label	OCC	%age	Label	OCC	%age	Label	OCC	%age	Label	OCC	%age
1	Virtual reality	513	19.8	Virtual reality	170	36.9	Industry 4.0 technologies	165	17.6	Industry 4.0 technologies	297	17.9
2	Augmented reality	455	17.6	Process simulation	55	11.9	Virtual reality	163	17.4	Augmented reality	284	17.1
3	Industry 4.0 technologies	451	17.4	Augmented reality	43	9.3	Augmented reality	135	14.4	Virtual reality	254	15.3
4	Smart manufacturing systems	164	6.3	Manufacturing industries	26	5.6	Manufacturing industries	55	5.9	Smart manufacturing systems	120	7.2
5	Manufacturing industries	141	5.4	Assembly information systems	20	4.3	Industrial internet of things	52	5.6	Digital twins	101	6.1
6	Industrial internet of things	139	5.4	Autonomous robots	19	4.1	Process simulation	50	5.3	Industrial internet of things	91	5.5
7	Process simulation	137	5.3	3d technologies	18	3.9	Smart manufacturing system	50	5.3	Manufacturing industries	77	4.6
8	Digital twin	104	4.0	Product development process	18	3.9	Cognitive ergonomics	46	4.9	Process simulation	73	4.4
9	Artificial intelligence	81	3.1	Industry 4.0 technologies	17	3.7	Autonomous robots	39	4.2	Cognitive ergonomics	68	4.1
10	Cognitive ergonomics	79	3.1	Virtual environment	17	3.7	Cyber physical systems	36	3.9	Artificial intelligence	66	4.0
11	Cyber-physical systems	79	3.1	Cognitive ergonomics	14	3.0	Digital twins	33	3.5	Autonomous robots	56	3.4
12	Autonomous robots	73	2.8	Digital technologies	13	2.8	3d technologies	30	3.2	Digital technologies	52	3.1
13	Human–robot interaction	64	2.5	Cyber-physical systems	11	2.4	Cross reality	29	3.1	Human–robot interaction	42	2.5
14	Assembly assistance systems	56	2.2	Computer aided manufacturing	10	2.2	Smart technologies	28	3.0	3d technologies	41	2.5
15	Smart factories	52	2.0	Manufacturing process	10	2.2	Assembly assistance systems	24	2.6	Cyber–physical systems	41	2.5

The third sub-period, which runs from 2021 to 2023, is the present phase. This sub-period contains an average of about 340 articles per year, and this phase saw the beginning of the significant increase. “Industry 4.0 technologies,” “augmented reality,” and “virtual reality” serve as the main subjects. They can be viewed as focused terms that become noticeable as top keywords over time. The terms "virtual reality," "augmented reality," "process simulation," “manufacturing industries," “autonomous robots," “3D technologies," “industry 4.0 technologies," “cognitive ergonomics," and “cyber-physical system" are the most frequently used keywords and are also important issues concerning the virtual reality domain. The terms appeared most frequently throughout all sub-periods (1992–2023).

When it reached a maximum of 378 in 2022, it had the biggest surge. But in 2023, it had fallen to 342 (see Fig. 2). The examination of the co-occurrence keywords suggests artificial intelligence and human-robot interaction as newly developed keywords during the third sub-period meaning that, these technologies started being used in this field in this period.

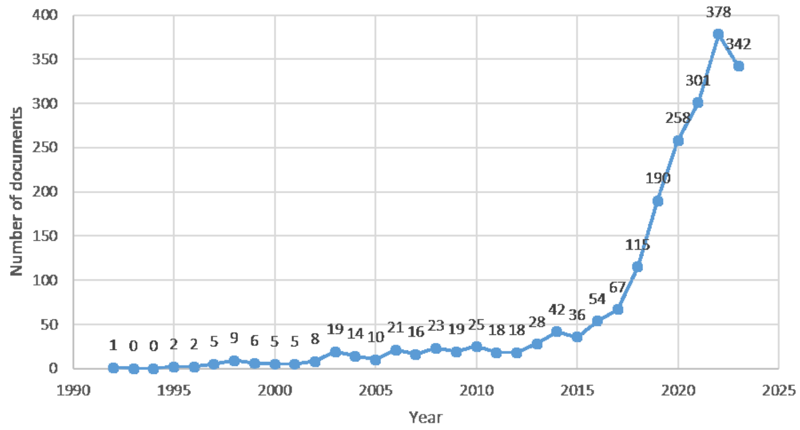

Fig. 2. Research growth in the connection between virtual reality and manufacturing industry

3.1.1. The Growing Trend of the Five Most Occurring Topics in Virtual Reality

The evolution of the most important subjects that have made the biggest contributions to the body of knowledge in earnings management is better understood by us and the readers thanks to the growth history. As a result, virtual reality experienced the highest growth rate of any occurrence in the first sub-period, at about 37 percent. The growth rate dropped to 17.4 percent in the period between 2018 and 2020; thereafter, it fell to 15.3 percent in the period between 2021 and 2023. Overall, the keyword had 20 percent growth(Table 1). Its high growth can be attributed to the findings by [45] that virtual reality enhances design review teams' communication by lessening the exclusion of professional groups; it may also speed up the evaluation process and solve user isolation difficulties [46]. However, problems occur with the interactive aspect of VR movement, necessitating the requirement for a "freeze" feature. Lack of data transfer standards prevents participants from requesting real-time computer-aided design changes in virtual reality [46]. [45] highlighted that industry standards were not supported by current VR development software, which highlights the need for further advancements. This was the stimulus for researchers to keep studying the topic, and so it became a highly used keyword.

Being among the top two concepts in virtual reality, augmented reality is a reasonably important concept that appears in all sub-periods and is reported by the literature to have the most impact. AR having 9.3 percent growth in the period between 1992 and 2020 was the second-highest percentage of all occurrences. Its growth rate rose to 14.4 percent in the period between 2018 and 2020. As a result, in the period between 2021 and 2023, it accounted for 17.1 percent of all co-occurrences. As a whole, 17.6 percent of all instances had an average growth rate for augmented reality (Table 1). The idea's growing appeal is a result of its possible application in the manufacturing industry [47]. According to [13], augmented reality plays a crucial role in providing real-time contextual accessibility to the vast amount of data generated by cyber-physical production systems for humans [22], and it is pivotal in implementing a human-centred approach to Industry 4.0 manufacturing [48], actively supporting intelligent manufacturing environments. Also recognized by the European Union as her key technology driving smart factories' development [13], as cited in Davies's study done in 2015, AR is instrumental in fostering cooperation and engagement among individuals and digital data-based manufacturing systems [14].

The amount of literature on "Industry 4.0 technologies" has been growing gradually over the years, growing at a pace of about 3.7 percent in the period between 1992 and 2017. In the period between 2018 and 2020, this rate increased to approximately 17.6 percent. Thereafter, the growth rate increased to 17.9 percent in the period between 2021 and 2023. The field of study is still relatively new, despite being the third fastest-growing term (Table 1), with 17.4 percent of all incidences. This sharp growth might indicate that there is enough interest in the subject among researchers. Chiarello et al. [6] uncovered that the realm of Industry 4.0 technology is not novel; however, it is exceptionally diverse, encompassing over 30 distinct technological domains [9]. Consequently, numerous stakeholders find themselves uneasy, lacking mastery over the entire spectrum of technologies, and experiencing challenges in communication with other domains [6]. This made researchers keep on studying the topic, which made the keyword appear at the top of the sub-periods.

In the first period, the word "smart manufacturing systems" didn’t appear in the top fifteen keywords. Nevertheless, its growth rate accounted for 5.3 percent of the co-occurrences in the period between 2018 and 2020 and a minor increase to 7.2 percent in the period between 2021 and 2023 (Table 1). Nonetheless, the closeness of smart manufacturing systems to other technologies [49] made it frequently mentioned in the period.

The incidence rate of the keyword "manufacturing industries" had inconsistence growth rates, as shown by growth rates of 5.6 percent in the period between 1992 and 2017, 5.9 percent in the period between 2018 and 2020, and dropped to 4.6 percent in the period between 2021 and 2023. With an average growth rate of 5.4 percent, this gain is gradually moving towards the 10 most frequently used terms. The manufacturing industries being the key term in the research title, all the papers were done in the field, and the technologies were supporting tools for sustainable development.

3.2. The Scope of the Most Productive Stakeholders in the Virtual Reality Literature

Gaining insight into the present state of research on virtual reality and the manufacturing industry can be facilitated by being aware of the authors and materials that contribute the most to the knowledge base. Additionally, it can assist in locating possible sources for fresh insights and investigations that might result in more advancements in the area. Moreover, it can give scholars a sense of which nations, publications, writers, and papers are the most significant and ought to be referenced for further details, as follows:

3.2.1. Productive Countries in the Virtual Reality Literature

Researchers can identify the active nations, comprehend contemporary patterns in research, on virtual reality and the manufacturing industry, and obtain insight into the standards being established for domain procedures by having knowledge of the countries that are very productive in this area. In addition, an analysis of the writers' geographic locations was carried out to determine the areas of academia where virtual reality and manufacturing industry research have received academic attention.

The study examined the authors' geographical locations to ascertain the areas of scholarly interest that have been concentrated on the connection between virtual reality and the manufacturing industry. The fact that this corpus of material was written in 114 different nations shows how popular the topic is around the world (Fig. 3). China (288), the United States (216), Italy (206), Germany (191), the United Kingdom (173), India (129), France (97), Sweden (91), Spain (81), Portugal (71), Brazil (61), Australia (53), Canada (52), Finland (52), and Greece (47) were the countries with the highest concentration of authorship, nevertheless. Researchers having ties to these fifteen nations provided more than half of the research on the connection between virtual reality and the manufacturing industry gathered for this review (Table 2).

Table 2 The Most Productive Countries by Number of Documents Published

Id	Label	Documents	Citations
1	China	288	5072
2	United States	216	8465
3	Italy	206	7933
4	Germany	191	4892
5	United Kingdom	173	10070
6	India	129	3391

7	France	97	3799
8	Sweden	91	1601
9	Spain	81	4151
10	Portugal	71	1958
11	Brazil	61	2913
12	Australia	53	2366
13	Canada	52	921
14	Finland	52	653
15	Greece	47	1324

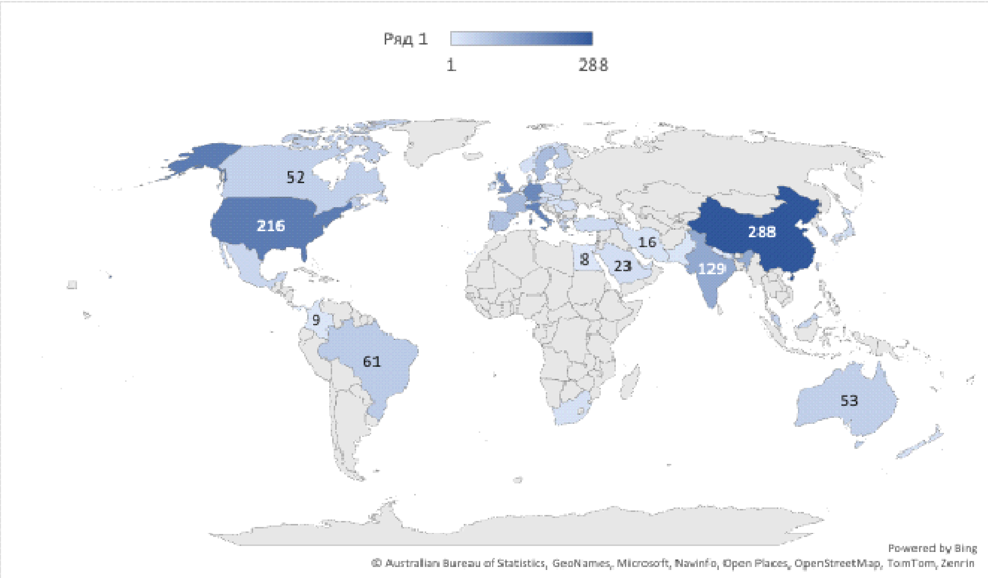

Fig. 3. Globally distribution of research in virtual reality literature

Additionally, as Table 3 illustrates, of the top fifteen nations by citation count, researchers from the UK (10,070), the USA (8,465), Italy (7,933), China (5,072), Germany (4,892), Spain (4,151), France (3,799), India (3,391), New Zealand (3,266), Brazil (2,913), Iran (2,374), Australia (2,366), Portugal (1,958), Mexico (1,893), and Turkey (1,836) contributed more than half of the virtual reality and manufacturing industry citations examined in this review.

Table 3 The Most Prolific Countries by number of citations

Id	Label	Documents	Citations
1	United Kingdom	173	10070
2	United States	216	8465
3	Italy	206	7933
4	China	288	5072
5	Germany	191	4892
6	Spain	81	4151
7	France	97	3799
8	India	129	3391
9	New Zealand	20	3266
10	Brazil	61	2913
11	Iran	16	2374
12	Australia	53	2366
13	Portugal	71	1958
14	Mexico	39	1893
15	Turkey	30	1836

As a result, the aforementioned nations made up the majority of contributors, wielding great influence in the field and greatly influencing academics through their research. In this instance, developed nations receive the majority of the research on virtual reality and the manufacturing industry, leaving developing nations uninformed (Tables 2, 3, and Fig. 3).

3.2.2. Examination of the Primary Contributing Journals

To stay abreast of the latest developments in research, as well as to discern the journals that are likely to accept their manuscripts and align with their research topics, researchers should acquaint themselves with the most influential journals in virtual reality literature. The 2,037 virtual reality papers in this instance were dispersed throughout 848 sources. However, the majority of those sources—55 percent—had several publications. The top fifteen journals, indicated in Table 4, have more than 33 percent of the corpus. With fifty-eight papers, the "lecture notes in computer science" journal was the most productive. However, 42,879 citations were shared by the 848 sources. Of all the sources, over twenty percent (not attached) had no citations, while the fifteen most productive provided over sixty percent of the citations (Table 4). With 3,145 citations from 42 publications, the "Journal of Manufacturing Systems" was the most prolific source; Table 4 lists the statistics for the other prolific sources.

Table 4 The most Productive sources in virtual reality

ID	Source	Documents	Citations
1	Journal of manufacturing systems	42	3145
2	Robotics and computer-integrated manufacturing	20	2781
3	Computers in industry	31	2316
4	International journal of production economics	9	2184
5	International journal of production research	22	1961
6	Engineering	3	1877
7	Computers and industrial engineering	17	1800
8	Journal of cleaner production	15	1636
9	IEEE access	26	1448
10	Journal of intelligent manufacturing	8	1140
11	International journal of advanced manufacturing technology	52	1117
12	Automation in construction	6	1074
13	Journal of manufacturing technology management	12	1013
14	Procedia CIRP	56	984
15	International journal of precision engineering and manufacturing	3	968

3.2.3. Analysis of Influential Authors in Virtual Reality Literature

The most prominent researchers in the connection between virtual reality and manufacturing industry literature are indicated in Table 5. Xu Xun had 2987 citations; Ghobakhloo, Morteza (1771); Zhong, Ray (1732); Klotz, Eberhard (1710); and Newman, Stephen (1710), among others exhibited in Table 5, are the most cited authors and, therefore, the most prolific ones. The authors' citations impact significantly and are realistic, as Table 5 demonstrates. The Scopus h-index, on the other hand, takes into account an author's entire body of scholarly work, which goes beyond the subject of the connection between virtual reality and the manufacturing industry [36]; thus, we haven't taken it into consideration. As a result, Table 5's citations are solely derived from the publications written by each author in our review domain.

Table 5 The most influential authors by Number of Citations

Id	Label	Documents	Citations
1	Xu, Xun	7	2987
2	Ghobakhloo, Morteza	5	1771
3	Zhong, Ray Y.	2	1732
4	Klotz, Eberhard	1	1710

5	Newman, Stephen T.	1	1710
6	Ayala, Néstor Fabián	3	1537
7	Romero, David	9	1479
8	Wuest, Thorsten	8	1409
9	Dalenogare, Lucas Santos	1	1401
10	Frank, Alejandro Germán	1	1401
11	Choi, Sangsu	7	1299
12	Gunasekaran, Angappa	4	1280
13	Noh, Sang Do	6	1215
14	Gursev, Samet	1	1044
15	Oztemel, Ercan	1	1044

3.2.4. Analysis of Influential Documents in Virtual Reality Literature

Based on all Scopus citations, Table 6 displays the papers that have been cited the most in virtual reality and manufacturing industry research. This examination aimed to assess the impact of researchers' contributions to the domain. Fifteen papers contained more than 13,103 citations. Considering how recent the connection between virtual reality and manufacturing industry literature is, these citations fall within a fair range. Therefore, the article [50], with 1,710 citations, stands out as the most frequently cited in this domain. It is among the top-cited articles displayed in Table 6. However, the most relevant and influential documents were not among the most cited. So, Table 7 displays the most relevant and influential articles on the influence of virtual reality on the manufacturing industry (discussed), along with their respective citation counts.

Table 6 The most prolific documents in Virtual Reality Literature

Authors	Title	Source title	Affiliations	Cited by
Zhong R.Y.et al. (2017)	Intelligent Manufacturing in the Context of Industry 4.0: A Review	Engineering	United Kingdom	1710
Frank A.G.et al. (2019)	Industry 4.0 technologies: Implementation patterns in manufacturing companies	International Journal of Production Economics	Brazil	1401
Oztemel E.& Gursev S. (2020)	Literature review of Industry 4.0 and related technologies	Journal of Intelligent Manufacturing	Turkey	1044
Kang H.S.et al. (2016)	Smart manufacturing: Past research, present findings, and future directions	International Journal of Precision Engineering and Manufacturing - Green Technology	South Korea	956
Jones D.et al. (2020)	Characterising the Digital Twin: A systematic literature review	CIRP Journal of Manufacturing Science and Technology	United Kingdom	847
Fuller A.et al. (2020)	Digital Twin: Enabling Technologies, Challenges and Open Research	IEEE Access	United Kingdom	803
Bhattacharjee N.et al. (2016)	The upcoming 3D-printing revolution in microfluidics	Lab on a Chip	Spain	789
Ghobakhloo M. (2020)	Industry 4.0, digitization, and opportunities for sustainability	Journal of Cleaner Production	Iran	777
Ghobakhloo M. (2018)	The future of manufacturing industry: a strategic roadmap toward Industry 4.0	Journal of Manufacturing Technology Management	Iran	775
Kamble S.S.et al. (2018)	Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives	Process Safety and Environmental Protection	United States	756
Lu Y.et al. (2020)	Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues	Robotics and Computer-Integrated Manufacturing	New Zealand	725
Shrouf F.et al. (2014)	Smart factories in Industry 4.0: A review of the concept and of energy management approached in production based on the Internet of Things paradigm	IEEE International Conference on Industrial Engineering and Engineering Management	Spain	675
Villani V.et al. (2018)	Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications	Mechatronics	Italy	623

Mittal S.et al. (2018)	A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs)	Journal of Manufacturing Systems	Mexico	612
Liu M.et al. (2021)	Review of digital twin about concepts, technologies, and industrial applications	Journal of Manufacturing Systems	China	610

Table 7 The prolific documents most relevant to virtual reality research (discussed)

Authors	Title	Source title	Cited by	Affiliations
Ong S.K. et al. 2008	Augmented reality applications in manufacturing: A survey	International Journal of Production Research	270	Singapore
Davila et al 2020	A research agenda for augmented and virtual reality in architecture, engineering and construction	Advanced Engineering Informatics	195	United Kingdom
Zorriassatine F. et al. 2003	A survey of virtual prototyping techniques for mechanical product development	Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture	184	United Kingdom
Syberfeldt A. et al. 2017	Augmented Reality Smart Glasses in the Smart Factory: Product Evaluation Guidelines and Review of Available Products	IEEE Access	159	Sweden
Liu X.F. et al. 2017	Cyber-physical manufacturing cloud: Architecture, virtualization, communication, and testbed	Journal of Manufacturing Systems	130	United States

[51] did an inclusive survey of augmented reality in “manufacturing activities,” such as assembly, maintenance, product development, and training. It assesses the software systems and hardware utilized in augmented reality, examines the primary research endeavors, and discusses the challenges associated with implementing AR in “manufacturing” and the current and future trends of AR technology. It also discusses some relevant issues, such as tracking, registration, view management, and user interface design, that affect the performance and usability of AR systems. The paper aims to provide useful insights and references for researchers, students, and engineers who are interested in using AR as a tool in manufacturing research and practice.

[52]’s study explored the applications of AR and VR in the AEC (architecture, engineering, and construction) industries. It also suggests a research program to close current gaps in necessary skills. 54 experts from 36 organisations participated in exploratory workshops, completed questionnaires, and reviewed relevant literature to gather data for the project. Design support, stakeholder engagement, design review, operations and management support, training, and construction support constitute the six use-cases for augmented reality and virtual reality in the AEC sectors that are defined in the study. For every use case, the study highlights the primary advantages, difficulties, and research areas. It also offers a research roadmap to direct future investigations. The purpose of the study is to educate scholars and practitioners as well as their potential in the future.

[53] presented a broad overview of virtual prototyping methods for mechanical product development, including the primary advantages, obstacles, and areas of ongoing research in this domain. Along with providing sources for more reading, the document also provides a summary of the many VP techniques, including fit and interference, testing and verification, manufacturing evaluation, and human factor analysis. The goal of the paper is to provide potential SME users with a thorough understanding of VP so they can choose VP technology wisely.

[54] presented a methodological paper that takes into account eighteen parameters that represent the unique needs and difficulties of the industrial work floor while assessing and choosing augmented reality smart glasses (ARSG). The procedure is also used in the article to evaluate twelve products that are currently on the market and suggest which one is ideal for the shop floor. In addition, the paper lists five areas that require deeper investigation in order to guarantee the successful application of ARSG in the smart factory.

[55] introduced a novel paradigm known as the CPMC (Cyber-Physical Manufacturing Cloud), enabling the direct operation and controlling of machines within a “manufacturing

cloud" through the Internet. This is achieved by seamlessly integrating "cloud computing" and "service-oriented technologies" into production processes. The study puts forth a virtualization approach for manufacturing resources, outlines a scalable and serviceable tiered style for the "CPMC," and establishes communication mechanisms across its layers using protocols such as TCP/IP, REST, and MTConnect. Furthermore, the study implements and assesses a fully functional "testbed" of CPMC grounded on the proposed style, which also shows the technology's viability and efficiency in a number of production scenarios.

3.3. Intellectual Structure of Virtual Reality Knowledge Base

Scientists utilizing scientific mapping review techniques have explored the "intellectual structure" across various academic disciplines [56]. The term "intellectual structure" denotes the fundamental theoretical and empirical research trajectories that define a particular field of study. Employing author co-citation analysis, a network map in VOSviewer was generated to illustrate the intellectual organization within the knowledge bases of virtual reality and the manufacturing industry.

A co-citation examination was used to examine how frequently writers were mentioned jointly in the reference lists of the 2,037 papers. Consequently, compared to Scopus citation, co-citation analysis explains a substantially greater corpus of literature.

Researchers utilizing co-citation analysis argue that authors sharing a similar research perspective are those frequently co-cited by their peers [41]. Furthermore, through the examination of "author co-citations," the VOSviewer software can generate a network map that visually represents shared attributes among the authors cited in our leveraged database [36], [43].

When VOSviewer was used with a minimum of 100 author co-citations as the criterion, 174 academicians (Fig. 4) were shown on the co-citation network. The larger nodes represent important researchers based on the number of co-citations. Scholars are divided into research topics by vibrant clusters based on co-citation links. 3D technologies and augmented reality in manufacturing (green cluster), industry 4.0 technologies and virtual reality (red cluster), and smart manufacturing (blue cluster) comprise the intellectual structure of the connection between virtual reality and manufacturing industry literature.

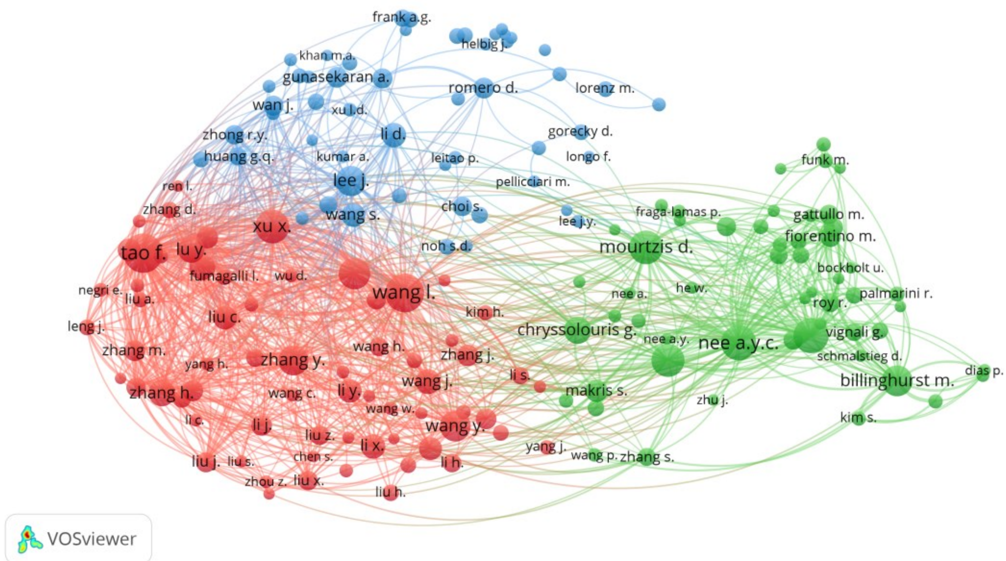

Fig. 4. Network map for the connection between virtual reality and manufacturing industry

With 734 co-citations, Tao, F., an expert on industry 4.0 technologies and virtual reality (the red cluster), has the greatest research field. Wang I., Xu X., and Liu, Y., researchers on the same topic, have 721, 581, and 522 co-citations, respectively. With 621, 618, 568, and 564 co-citations, the 3D technologies and augmented reality in manufacturing experts Nee A. Y. C., Ong S. K., Mourtzis D., and Wang X., respectively (the green cluster), marked the next cluster.

Table 8 The Most Collaborative Authors by Number of Co-citations

Id	Label	Cluster	Citations
1	Tao F.	1	734
2	Wang L.	1	721
3	Nee A.Y.C.	2	621
4	Ong S.K.	2	618
5	Xu X.	1	581
6	Mourtzis D.	2	568
7	Wang X.	2	564
8	Liu Y.	1	522
9	Billinghurst M.	2	492
10	Wang Y.	1	491
11	Lee J.	3	485
12	Zhang Y.	1	476
13	Chryssolouris G.	2	414
14	Zhang H.	1	394
15	Lu Y.	1	386

Then, with 485, 337, and 333 co-citations, Lee J., Li D., and Wang S., respectively, were specialists in smart manufacturing (the blue cluster). The lists of the top 15 writers are displayed in Table 8.

3.4. Topical Concentrations in Virtual Reality Knowledge Base

Using keyword analysis, the themes discussed in the connection between virtual reality and manufacturing industry literature were examined. Using VOSviewer, we first determined which terms were most frequently used. The terms "virtual reality" with 513 occurrences, "augmented reality" (455), “industry 4.0 technologies” (451), “smart manufacturing systems” (164), “manufacturing industries” (141), “industrial internet of things” (139), "process simulation" (137), and “digital twins” (104), among others, are the most referenced keywords in all periods and are also important issues concerning the virtual reality domain. The writers’ co-citations, which indicated that all of the clusters were related to the connection between virtual reality and the manufacturing industry and that the word therefore became significant, are supported by this pattern of results (Fig. 5).

Subsequently, employing a threshold of a minimum of 5 co-occurrences, we created a "chronological keyword map" (Fig. 5) in VOSviewer [43]. The chronological co-word analysis scrutinizes the distribution of keywords over time concerning the paper publication date. The darker nodes reflect themes that were common in the past, whereas the yellower or lighter-tinted bubbles reflect the most current issues of interest to researchers in this discipline. This map can be interpreted by looking at the node size (occurrence), colour (recentness), and position (connection to other themes).

At the core of the map, the topic of "virtual reality" has the greatest connections to other subjects and is currently of interest. This conclusion is consistent with the discussion around the conceptual framework of the knowledge base, wherein the five study fields gave significant weight to the connection between virtual reality and the manufacturing industry.

An author keyword examination was used to decide the future course of the virtual reality study. After extracting the author keywords from our database of 2,037 relevant articles, an author keyword network was constructed using the VOSviewer programme. To get logical data, we imposed a condition of at least five co-occurrences of keywords. Of the 4,238 key words, 165 satisfied our requirements. It was found that the most common keyword, "virtual reality," appeared 513 times, so it is the largest node in the network, based on the map (Fig. 5).

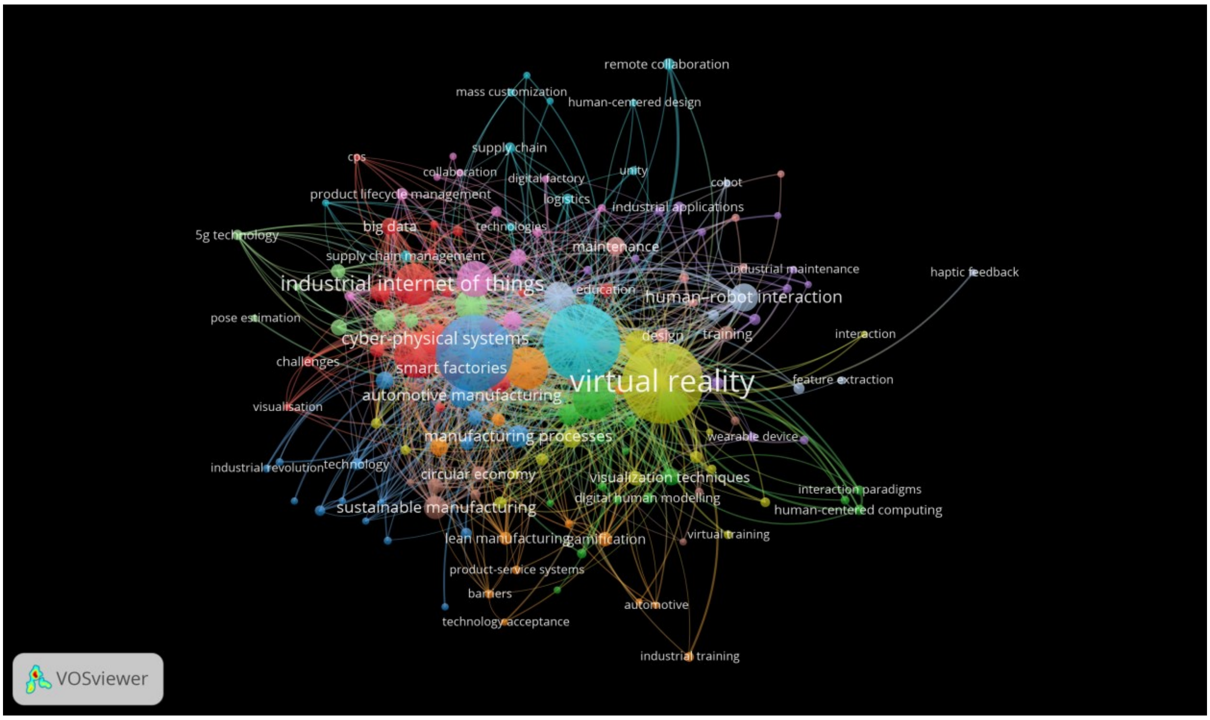

Fig. 5. Topical concentration map for research in virtual reality literature

Keywords that have similar colours together signify that they belong to the same group. This suggests that different aspects of "virtual reality" have been addressed. The examination of the keyword network produced several conclusions. In summary, it first showed that augmented reality, manufacturing industries, smart manufacturing systems, artificial intelligence, industry 4.0 technologies, 3D technologies, industrial internet of things, and process simulation are the ones that are generally studied in terms of the studied domain.

4. Conclusion, Research Gap, and Limitations

4.1. Conclusion

The scope of the connection between virtual reality and manufacturing industry literature is demonstrated by this review of works. Despite the fact that the first pertinent academic paper published on the Scopus database was in 1992, the majority was published in the last decade. This is because virtual reality is perceived as a still-new research area, despite the fact that virtual reality is becoming increasingly important to manufacturing organisations' value [8]. Nevertheless, there has not been much research on the connection between virtual reality and the manufacturing industry.

This study represents an initial effort to arrange and add up the literature that science has to offer about the connection between virtual reality and the manufacturing industry. Several quantitative bibliometric investigations have been carried out to achieve this, utilizing software packages and computational methodologies that facilitate contribution in the process of knowledge generation. Gaps for further studies that consider the subject's active growth were identified, offer a thorough impression of the literature on virtual reality, and suggest some possible research avenues in this way.

Theoretically, by looking at how virtual reality in the manufacturing industry has developed, current tendencies, and recently discovered topics that are underrepresented and require further research, this study advances understanding of virtual reality in manufacturing.

It could empower researchers to develop a thorough comprehension of a topic or benefit from the citation network's dissection into its component elements. This can help researchers by pointing out the most researched aspects of the topic, emerging patterns, and evolutionary orientations.

4.2. Research gaps

The terms "virtual reality," “augmented reality," “process simulation," “industrial internet of things," “industry 4.0 technologies," and “3D technologies" are still very popular and are being explored at the highest level compared to other concepts because the use of digital technologies in manufacturing is moving at a high pace.

During the most recent sub-periods (2018–2023), several terms were introduced. These consist of the “industrial internet of things,” “smart manufacturing systems,” and “digital twins.” These terms require further research because they are still new but important in the use of digital technology in manufacturing industries. Furthermore, cross-reality, smart technologies, and assembly assistance systems appeared in their first period, and in the next period, they disappeared. Due to their attachment to the research topic and their newness, they still need further research.

4.3. Limitations

The restrictions on bibliometric techniques, which are appropriate to our investigation, are not immune. At the outset, despite the benefits of the Scopus database, there is a possibility that pertinent papers exclusively accessible through other databases (such as ABI, Web of Sciences, and Inform/ProQuest) might have been overlooked, a common challenge in many bibliometric studies [57]. Also, documents like national periodicals, books, editorial content, and conference proceedings are omitted from this search strategy, even though they might be just as significant in the connection between virtual reality and the manufacturing industry [58]. Lastly, co-occurrence, co-citation, and citations were used, just like [59]. To complement our results, other bibliometric techniques, such as bibliographic coupling, may be applied. Therefore, the limitations indicated above offer endorsements for future research that aims to reinforce or improve upon them.

Conflicting interests

Regarding this research, the authors state that there are no possible conflicts of interest.

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