SILESIAN UNIVERSITY OF TECHNOLOGY PUBLISHING HOUSE

SCIENTIFIC PAPERS OF SILESIAN UNIVERSITY OF TECHNOLOGY 2023
ORGANIZATION AND MANAGEMENT SERIES NO. 181

VR TECHNOLOGY IN MANUFACTURING PROCESSES – A BIBLIOMETRIC ANALYSIS

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Purpose: The aim of the article is to understand how research and practices related to the use of VR in production processes are developing. As well as providing information on the diversity of VR applications in industry.
Design/methodology/approach: The bibliometric analysis is based on data from the Scopus database and Web of Science, focused on research and scientific publications related to the use of VR in the context of manufacturing processes. The subject scope of the article includes identifying, among other things, the dominant authors and organizations in the analyzed topic. Analysis of keywords and visualization of their connections using VOSviewer software, and identification of the resulting topic clusters. In addition, identification of research trends and areas for further work.
Findings: The bibliometric analysis conducted reveals several research trends and research areas related to the use of virtual reality technology in the manufacturing industry. The research includes, but is not limited to, the exploration of innovative teaching and training delivery methods and the impact of VR on manufacturing processes. In addition, they include the development of digital manufacturing, the creation of smart factories in line with the concept of Industry 4.0. The trends reflect the drive to use VR as a tool for optimization, achieving industrial sustainability goals and shaping the future of manufacturing.
Research limitations/implications: Limitations are due to the very nature of bibliometric research and the use of two databases for publication selection (Scopus, Web of Science).
Originality/value: The value of the article lies in providing information that can be useful to practitioners and researchers interested in this topic. The work identifies and discusses specific research areas and trends related to the use of VR in the manufacturing industry. Includes analysis of new approaches and innovative methods that are emerging in research.

Keywords: bibliometric analysis, Virtual Reality, Industry 4.0, digital factory, Artificial Intelligence.

Category of the paper: Research paper, Literature review.

1. Introduction

Virtual reality (VR) is not a new idea, but some of the innovative VR technologies that have recently appeared in the gaming industry are now being tested and increasingly implemented in the manufacturing industry. (de Giorgio et al., 2017) VR is the induction of a specific behavior in an organism using artificial sensory stimulation, with minimal or no awareness of this intervention. Virtual reality consists of four key components. The first is “Targeted Behavior”, which includes virtual experiences designed by the creators, such as the ability to move, explore, and interact. The next component is “Organism”, which refers to both the VR user and other forms of virtual life such as humans, animals, and chatbots. The third element is "Artificial Stimulation of the Senses," which means the ability to recreate sensory experiences using modern engineering technologies. The final component is “Awareness”, which ensures seamless user interaction with the virtual world, allowing the user to fully immerse themselves in this reality. A VR system sustains a perceptual illusion for the organism (LeValle, 2023). Virtual reality and augmented reality (AR) are considered the most revolutionary technologies of the 21st century. By providing computer-generated visual stimuli, these technologies are able to immerse our minds in experiences that we temporarily accept as subsequent real versions of reality (Nayyar et al., 2018). With increasingly dependable hardware and more user-friendly software, the operation of VR systems is becoming more straightforward. Nevertheless, due to the complex interaction of these technologies, VR is not yet a plug-and-play solution. While it's possible that in the future, people will be as comfortable with VR systems as they are with modern desktop workstations, we haven't reached that point yet (Berg et al., 2017). There are many publications in the literature addressing virtual reality. However, no attempt has been made to provide a comprehensive picture of the current state of research on virtual reality in manufacturing processes from a bibliometric perspective. The study included a bibliometric analysis of publications from 2012 to 2022 available in Scopus and Web of Science databases. Keyword analysis is one of the methods used in bibliometric analysis, which involves analyzing words found in the title, abstract or keywords of scientific publications. Keywords are words or phrases that best describe the content of a publication and are used to index publications in scientific databases. Keyword analysis identifies the most frequently occurring words or phrases in a given publication or an entire set of publications, which can help assess trends or developments in a given area of research. This can be useful, among other things, to determine what topics are most frequently researched in a given scientific field or what are the most important research directions in a given area.

The work presents new approaches and methods that appear in the literature regarding the use of VR in the manufacturing industry. This publication answers the following question:

- What are the main trends in the application and development of virtual reality technology in manufacturing processes?
- What priorities and activities will be important in the context of using virtual reality technology in industry? The article consists of five parts. An introduction describes the VR technology. The second part presents the research methods. The third part is a description of the results obtained from the research and presents the results of the study. Section fifth undertakes a discussion. The last part summarizes the paper and suggests directions for future research.

2. Methods

A bibliometric analysis method was used to review the literature on virtual reality technology in manufacturing processes. It is a research method that uses data contained in scientific publications, such as the number of citations, the number of publications, the number of authors, etc., to assess the impact or scientific reach of a given researcher, institution or field of research. It can be used for various purposes, such as assessing specialist knowledge, assessing the quality of scientific publications or assessing the impact of scientific institutions on the scientific community. Bibliometric analysis is often used in the social sciences and humanities, but can also be used in other scientific fields such as medicine or engineering. This method is often used by researchers at the initial stage of interest in a selected topic. Based on many available publications, it enables identification, synthesis, analysis and critical content analysis (Bornmann, Haumschild, 2017; Keathley, Herring et al., 2016).

Figure 1 shows the operationalization of the process used in the article by bibliometric analysis.

The research methodology used consists of 7 stages, which include: selection of bibliographic databases (stage 1), selection of keywords (stage 2), criteria limiting the search for publications (stage 3), data extraction and selection (stage 4), analysis of the set of publications (stage 5), identification of research areas (stage 6) and creation of thematic clusters (stage 7). During the first stage, the bibliographic databases Scopus and Web of Science were chosen because of their accessibility, thematic breadth and wide range of publications within all scientific disciplines.

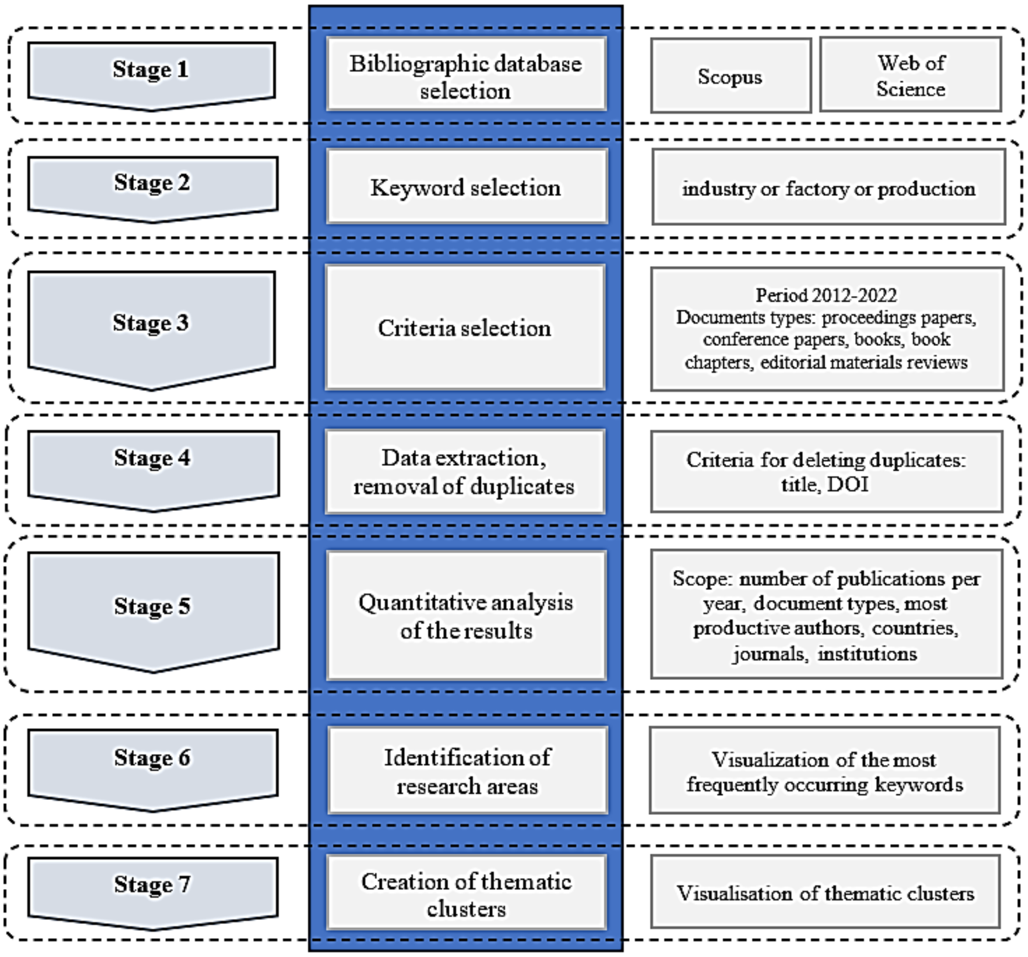

Figure 1. Methodology of bibliometric analysis.

Source: author's work.

The bibliometric analysis included publications related to "Virtual Reality." The first step of the research was to include publications containing this phrase in every type of document, while the next step was only in titles, abstracts and keywords. Keywords such as "industry", "factory", "production" were selected and the search for publications was narrowed to the period 2012-2022. Proceedings papers, books, book chapters, reviews, editorials were selected for further analysis. Other types of documents like note and short survey were not considered. The results are shown in the table (Table 1).

A first search for the phrase "Virtual reality" in the Scopus database generated 286706 publications, while Web of Science generated 88598 publications. The initial area represents a huge number of publications, also unrelated to the research direction. Therefore, in the second attempt, the search was limited only to publications that contained the indicated phrase in the title, abstracts and keywords. This yielded 104057 publications in the Scopus database and 78946 in Web of Science. Taking into account another limit of the criteria (the occurrence of the words "industry" or "factory" or "production"), 9083 and 4054 publications were obtained. Given that this is still a huge number of records, another limit was applied in the form of searching for the phrase in the title only. This approach significantly refined the filtering of the data. The results are shown in the table (Table 1).

Table 1.
Preliminary and principal search results

Stage	Scopus	Web of Science
First research query	ALL ("Virtual Reality")	ALL ("Virtual Reality")
Number of articles before inclusion criteria	286 706	88 598
Number of articles after inclusion criteria	77 716	7 080
Second research query	TITLE-ABS-KEY ("Virtual reality")	TITLE-ABS-KEY ("Virtual reality")
Number of articles before inclusion criteria	104 057	78 946
Number of articles after inclusion criteria	9 083	4 054
Third research query	TITLE ("Virtual reality")	TITLE ("Virtual reality")
Number of articles before inclusion criteria	22 125	26 460
Number of articles after inclusion criteria	267	162

Source: author's work based on the Scopus and Web of Science databases.

Finally, after applying the adopted restriction in the form of document type and taking into account the criteria, 267 and 162 records were obtained (Table 1). Files in "csv" format were generated from each of the databases. The downloaded files were merged into one, after removing duplicates the content was obtained in the form of 284 records.

Then, based on the received file, an analysis was made of the number of publications in the 2012-2022 interval, the most productive authors, countries, organizations, journals. The most cited articles were identified. Then, based on the received file, an analysis was made of the number of publications in the 2012-2022 interval, the most productive authors, countries, organizations, journals. As well as the most cited articles were identified. Using VOSviewer software, the most frequent keywords were obtained, and a map of the co-occurrence of keywords related to "Virtual Reality" was presented. A thesaurus file was prepared to eliminate terms with the same meaning (e.g. VR, Virtual Reality) or not relevant to the study (e.g. tourism). The resulting data was analyzed and subject areas were identified that represented the main and emerging research directions.

3. Results

The first stage shows the interest in the topic, in the form of the number of publications over the years analyzed (Figure 2).

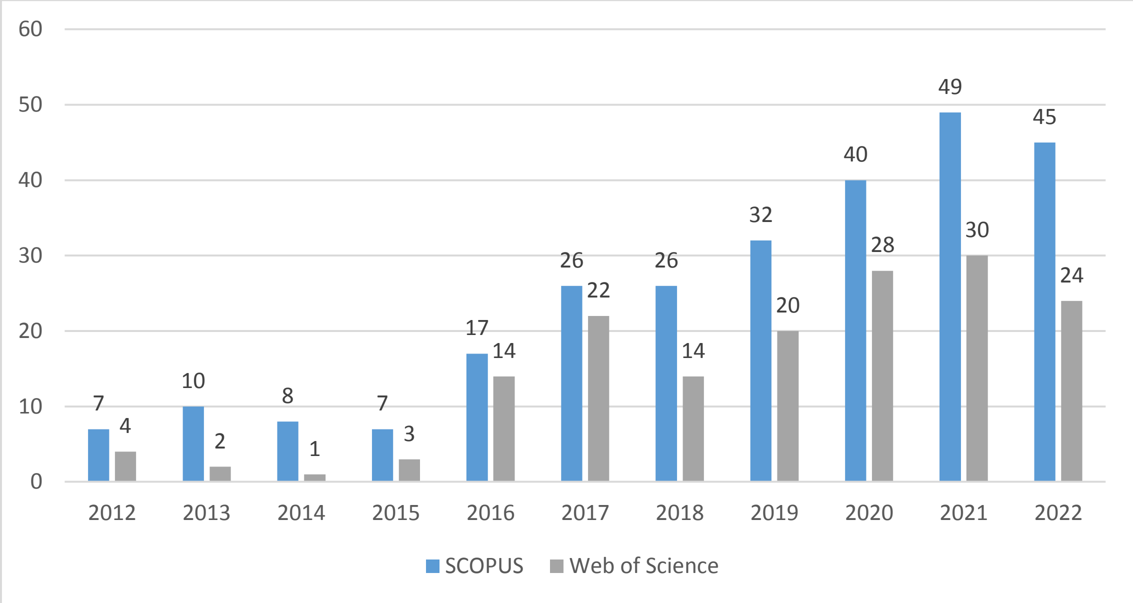

Figure 2. Number of publications in the field of VR technology in manufacturing processes in Scopus and Web of Science databases (indexed from 2012 to 2022).

Source: author's work based on the Scopus and Web of Science databases.

In the case of both Scopus and Web of Science databases, numerous publications appeared between 2012 and 2022, with the largest number in 2021. In 2012-2015, they occurred in small numbers, even sporadically.

Figure 3 shows the structure of publications by document type.

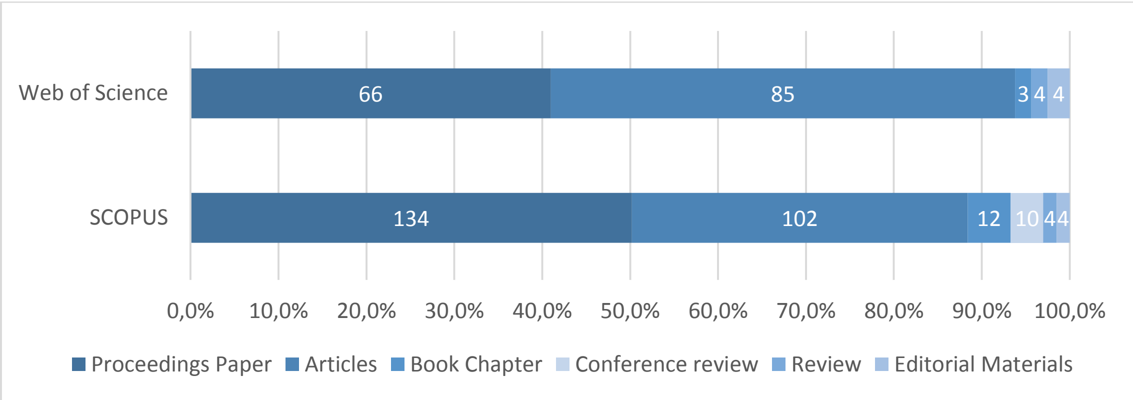

Figure 3. Type of documents of publications in the field of VR technology in manufacturing processes in Scopus and Web of Science databases (indexed from 2012 to 2022).

Source: author's work based on the Scopus and Web of Science databases.

Both databases were dominated by proceedings paper type publications and articles (Scopus - 88.4%, Web of Science - 93.8%). Most publications in the Scopus database are assigned to Computer Science (55%) and Engineering (51%). This is followed by (16%) Social Sciences, (15%) Mathematics and (10%) Business, Management and Accounting. Meanwhile, in the Web of Science database, 25% are assigned to the Engineering Electrical Electronic category, 21% to Computer Science Artificial Intelligence, 16% each to Engineering Manufacturing and

Computer Science Theory Methods. Another 14% in the Computer Science Interdisciplinary Applications category. Nomenclature between the databases varies.

The authors who published the highest number equal to 6 were Palmisano, Pedram and Perez. They were also the authors with the highest average number of citations per publication equal to 2.1%. This was followed by Farrelly with 5 published papers and an average number of citations per publication of 1.7%.

Table 2 shows a detailed summary of the data.

Table 2.
Most productive authors, countries, organisations and journals

No.	Item	NP	%	Average citation count	
				Scopus	Web of Science
Authors					
1	Palmisano, S.	6	2,1%	4,3	N/A
2	Pedram, S.	6	2,1%	4,3	0
3	Perez, P.	6	2,1%	4,3	N/A
4	Farrelly, M.	5	1,7%	4,4	N/A
5	Zawadzki, P.	4	1,4%	12,5	9,3
6	Agethen, P.	3	1,0%	14,7	12
7	Cardona-Reyes, H.	3	1,0%	0,0	0
8	Górski, F.	3	1,0%	12,7	9
9	Pfeiffer, T.	3	1,0%	18,3	9
10	Rukzio, E.	3	1,0%	14,7	12
Countries					
1	China	45	15,4%	5,64	8,6
2	United States	30	10,3%	31,4	36,16
5	Germany	18	6,2%	17,28	16,91
4	United Kingdom	14	4,8%	31	34,22
6	Spain	12	4,1%	18,67	13,82
3	Australia	11	3,8%	4,18	3,28
8	Italy	11	3,8%	28,81	23,89
7	Poland	9	3,1%	12	8,29
9	Sweden	9	3,1%	16,7	11,86
10	France	9	3,1%	5	5,2
Organisations					
1	University of Wollongong	6	2,1%	4,3	N/A
2	Politechnika Poznanska	4	1,4%	12,5	9
3	Center for Research in Mathematics	3	1,0%	0	N/A
4	Mines Rescue	3	1,0%	6	N/A
5	Chalmers University of technology	3	1,0%	19,7	15,5
6	The Royal Institute of Technology KTH	3	1,0%	18,3	12
7	Universidad Autónoma de Aguascaliented	3	1,0%	0	0
8	Universität Ulm	3	1,0%	14,67	12
9	Universität Bielefeld	3	1,0%	18,33	14,33
10	University of York	3	1,0%	7,7	N/A

Cont. table 2.

Journals					
1	Virtual Reality	2	0,7%	229	166,5
2	Concurrent Engineering Research and Applications	1	0,3%	196	140
3	Advanced Engineering Informatics	1	0,3%	136	100
4	IEEE Transactions on Human-Machine Systems	1	0,3%	136	100
7	Robotics and Computer-Integrated Manufacturing	1	0,3%	112	75
6	International Journal of Mining Science and Technology	1	0,3%	109	83
5	Advances in Engineering Software	1	0,3%	101	71
9	Data	1	0,3%	86	68
8	Journal of Computing and Information Science in Engineering	1	0,3%	75	49
10	Procedia Manufacturing	3	1,0%	49,33	N/A

Note. NP – number of publications, [%] – the percentage of the total number of publications (284), N/A – not applicable.

Source: author's work based on the Scopus and Web of Science databases.

The largest number of publications came from China (45 publications) and the United States (30 publications). Considering the affiliation/organization of the authors, the most publications came from the University of Wollongong (6 publications). The organization with the highest average number of citations in the Scopus database and Web of Science is Chalmers University of technology, followed by Universität Bielefeld. Among the most productive journals is Virtual Reality (2 publications), at the same time being the highest average cited in both databases. The total number of citations of publications on Virtual Reality in the Scopus database was 458, and in the Web of Science database was 327. The following journals were ranked next: Concurrent Engineering Research and Applications, Advanced Engineering Informatics, IEEE Transactions on Human-Machine Systems, Robotics and Computer-Integrated Manufacturing, and International Journal of Mining Science and Technology, Advances in Engineering Software, Data.

Among the most-cited publications in the Scopus (451) and Web of Science (327) databases was the 2017 article "Industry use of virtual reality in product design and manufacturing: a survey" by Berg and Vance published in the journal Virtual Reality. Next also highly cited by both databases (196 and 140) was a 2015 article by Choi et al. titled "Virtual reality applications in manufacturing industries: past research, present findings, and future directions" I published in the journal Concurrent Engineering Research and Applications. Next in the Scopus database (136) highly cited is "Construction industry offsite production: A virtual reality interactive training environment prototype" by Goulding et al. from 2012, while in the Web of Science database (100) it is "Discrete Event Simulation and Virtual Reality Use in Industry: New Opportunities and Future Trends" by Turner et al. published in IEEE Transactions on Human-Machine Systems in 2016. The full list of the 19 most-cited publications is shown in the table (Table 3).

Table 3.
The most cited articles about VR technology in industry

No.	Number of citations		Authors	Article title	Journal
	Scopus	Web of Science			
1	451	327	(Berg, Vance, 2017)	Industry use of virtual reality in product design and manufacturing: a survey	Virtual Reality
2	196	140	(Choi et al., 2015)	Virtual reality applications in manufacturing industries: Past research, present findings, and future directions	Concurrent Engineering Research and Applications
3	136	100	(Goulding et al., 2012)	Construction industry offsite production: A virtual reality interactive training environment prototype	Advanced Engineering Informatics
4	136	100	(Turner et al., 2016)	Discrete Event Simulation and Virtual Reality Use in Industry: New Opportunities and Future Trends	IEEE Transactions on Human-Machine Systems
5	134	88	(Damiani et al., 2018)	Augmented and virtual reality applications in industrial systems: A qualitative review towards the industry 4.0 era	IFAC-PapersOnLine
6	112	75	(Roldán et al., 2019)	A training system for Industry 4.0 operators in complex assemblies based on virtual reality and process mining	Robotics and Computer-Integrated Manufacturing
7	109	83	(Zhang, 2017)	Head-mounted display-based intuitive virtual reality training system for the mining industry	International Journal of Mining Science and Technology
8	101	71	(Manca et al., 2013)	Bridging between Virtual Reality and accident simulation for training of process-industry operators	Advances in Engineering Software
9	97	N/A	(Nayyar et al., 2018)	Virtual Reality (VR) & Augmented Reality (AR) technologies for tourism and hospitality industry	International Journal of Engineering and Technology(UAE)
10	93	60	(Eschen et al., 2018)	Augmented and Virtual Reality for Inspection and Maintenance Processes in the Aviation Industry	Procedia Manufacturing
11	86	68	(Noghabaei et al., 2020)	Trend analysis on adoption of virtual and augmented reality in the architecture, engineering, and construction industry	Data
12	86	60	(Salah et al., 2019)	Virtual reality-based engineering education to enhance manufacturing sustainability in industry 4.0	Sustainability (Switzerland)
13	75	49	(Berg, Vance, 2017)	An Industry Case Study: Investigating Early Design Decision Making in Virtual Reality	Journal of Computing and Information Science in Engineering
14	72	57	(Delgado et al.., 2020)	Augmented and Virtual Reality in Construction: Drivers and Limitations for Industry Adoption	Journal of Construction Engineering and Management
15	70	41	(Liagkou et al., 2019)	Realizing Virtual Reality Learning Environment for Industry 4.0	Procedia CIRP

Cont. table 3.

16	67	53	(Dunnagan et al., 2020)	Production and Evaluation of a Realistic Immersive Virtual Reality Organic Chemistry Laboratory Experience: Infrared Spectroscopy	Journal of Chemical Education
17	62	45	(Joshi et al., 2021)	Implementing Virtual Reality technology for safety training in the precast/ prestressed concrete industry	Applied Ergonomics
18	59	52	(Leung et al., 2020)	A fad or the future? Examining the effectiveness of virtual reality advertising in the hotel industry	International Journal of Hospitality Management
19	46	42	(Xie et al., 2018)	The consensus of probabilistic uncertain linguistic preference relations and the application on the virtual reality industry	Knowledge-Based Systems

Note: N/A – not applicable.

Source: author's work based on the Scopus and Web of Science databases.

As part of the bibliometric analysis, the most frequently occurring keywords related to the topic of "Virtual Reality" were extracted using VOSviewer software. A total of 33 words or phrases were generated that occurred at least 3 times in the keywords included in the 284 articles analyzed. The set included words with the same meaning as the abbreviations VR and Virtual Reality or AR and Augmented Reality. A thesaurus file was prepared to organize the data set. The notation of terms and abbreviations with the same meaning was standardized, and words irrelevant to the analysis were removed (for example, "tourism", "serious game" "covid-19"). The final file contained 29 keywords. Figure 4 shows the most popular ones.

Figure 4. The most frequently occurring key words.

Source: elaborated by the author using WordArt.

The most frequently occurring keywords related to VR technology included terms related to technology (virtual reality had 166 occurrences in this set, augmented reality 26 occurrences, mixed reality – 3, technology – 6), industry (industry 4.0 – 27, engineering – 6, smart factory – 6), science (virtual reality training – 20, education – 13), simulation 8.

The VOSviewer program allowed for the creation of a graphical representation of a network (Figure 5), illustrating the frequency of occurrence of individual terms in the bibliographic descriptions of articles selected for analysis and showing how often these terms co-occurred. This visualization presents each word as a point, with its size and font size reflecting the frequency of its occurrence in the analyzed texts. The program also enabled the grouping of related terms into clusters, which were differentiated using different colors. These clusters represent terms that often appeared together, although this does not exclude their co-occurrence with other terms.

The VOSviewer program allowed for the generation of a network (Figure 5) showing how frequently individual items appeared in the bibliographic descriptions of articles selected for analysis and how often specific elements co-occurred. Each point on this network represents a word or phrase, with its size and font size reflecting the frequency of occurrence of that element. The program also enabled the grouping of elements into clusters, which were then differentiated by different colors. It is worth noting that elements from the same clusters often appeared together, but this did not exclude their simultaneous occurrence with other terms. Additionally, the closer the circles on the graph were to each other, the more frequent the co-occurrence of terms, and the thickness of the lines connecting them reflected the degree of significance of this co-occurrence.

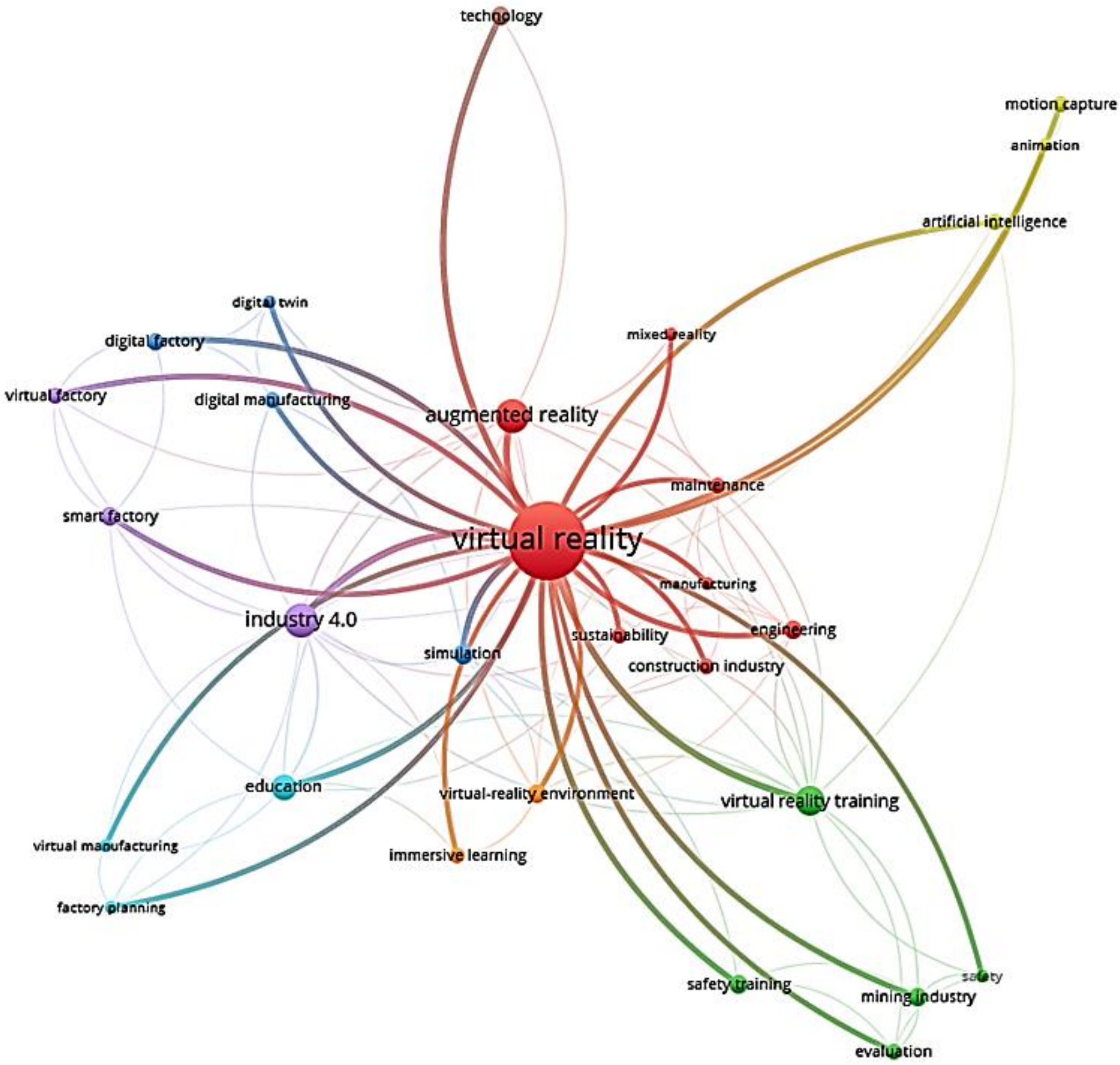

Figure 5. Keyword co-occurrence map on VR technology in industry.

Source: author's work based on the Scopus and Web of Science databases.

It is worth paying attention to the emerging new terms related to VR technology in recent years, which contribute to creating new thematic areas (Figure 6).

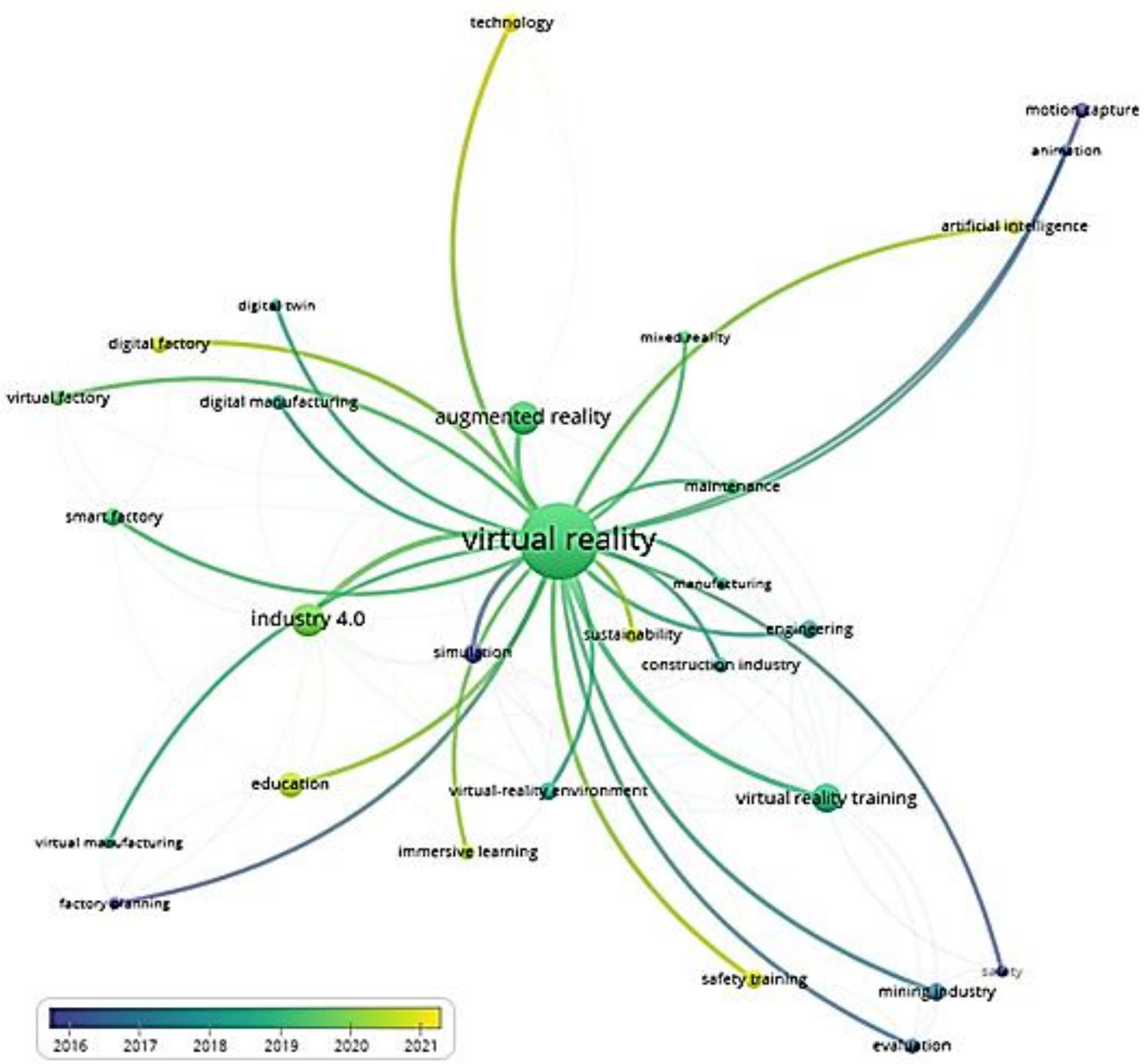

Figure 6. Keyword co-occurrence map on VR technology in industry in time perspective.
Source: author's work based on the Scopus and Web of Science databases.

The beginnings of discussing virtual reality in the manufacturing industry in literature were associated with topics such as factory planning, simulation, evaluation, and motion capture. From 2020 to the present, there has been a significant increase in the exploration, analysis, presentation, and interest in areas of education, immersive learning, training, digital factory, and artificial intelligence. The emergence of new terms and clusters indicates the development and growing interest in these topics.

4. Discussion

The VOSviewer program enabled the identification of 7 main thematic clusters, the so-called Clusters. Table 4 presents the thematic threads within each cluster along with examples of publications.

Table 4.
Main thematic clusters of the use of VR technology in manufacturing processes

No.	Cluster name	Key words	Selected publications
1.	Technology and Sustainability	augmented reality	Damiani et al., 2018; Eschen et al., 2018; Leung et al., 2020; Nayyar et al., 2018; Noghabaei et al., 2020
		construction industry	Noghabaei et al., 2020; Delgado et al., 2020
		engineering	Berg, Vance, 2017; Goulding et al., 2012; Noghabaei et al., 2020; de Giorgio et al., 2017
		maintenance	Eschen et al., 2018; Barkokebas et al., 2019; Rendeniya et al., 2019
		manufacturing	Choi et al., 2015; Salah et al., 2019
		mixed reality	Eschen et al., 2018; Leung et al., 2020
		sustainability	Salah et al., 2019; Krupnova et al., 2020
		virtual reality	Noghabaei et al., 2020; Bellalouna, 2020; Carretero et al., 2021; Checa et al., 2022
		technology	Xie et al., 2018
2.	Safety and Training	evaluation	Pedram et al., 2019
		mining industry	Roldán et al., 2019; Zhang, 2017; Pedram et al., 2014
		safety	Paszkiewicz et al., 2021; Pedram et al., 2014; Pedram et al., 2017; Pedram et al., 2018
		safety training	Joshi et al., 2021; Manca et al., 2013; Zhang, 2017
		virtual reality training	Górski et al., 2018; Zawadzki et al., 2019
3.	Digital Production and Simulation	digital factory	Shamsuzzoha et al., 2021; Chandra et al., 2021; Schlegel et al., 2022
		digital manuacturing	Dahl et al., 2017
		digital twin	Kuts et al., 2017; Kritzler et al., 2017
		simulation	Turner, 2016; Manca et al., 2013; Firu et al., 2020; Jiang, 2012
4.	Animation Technology and Artificial Intelligence	animation	Yan, 2021; Ji, Zhang, 2016
		artificial intelligence	Butean et al., 2019
		motion capture	Novak-Marcincin et al., 2013; Spada et al., 2012
5.	Industry 4.0 and Smart Factories	industry 4.0	Roldán et al., 2019; Turner et al., 2016; Nayyar et al., 2018; Berg, Vance, 2017; Choi et al., 2015; Eschen et al., 2018; Xie et al., 2018; Pandya et al., 2018; Żywicki et al., 2018, Liagkou et al., 2019
		smart factory	Żywicki et al., 2018,
		virtual factory	Damiani et al., 2018
6.	Education and Production Planning	education	Salah et al., 2019; Dunnagan et al., 2020; Paszkiewicz et al., 2021; Tovar et al., 2020; Tan et al., 2022
		factory planning	Menck et al., 2012; Gong et al., 2019; Bellalouna, 2020
		virtual manufacturing	Abdelkhalik, Elngar 2020; Choi et al., 2015
7.	Science and Virtual Reality Environments	immersive learning	Dunnagan et al., 2020; Berg, Leif, Judy, 2017; Radhakrishnan et al., 2021
		virtual-reality environment	Roldán et al., 2019; Liagkou et al., 2019; Horejsi et al., 2020; Ulmer et al., 2020

Source: author's work based on the Scopus and Web of Science databases.

The "Technology and Sustainability" cluster focuses on virtual and augmented reality technologies used in engineering, maintenance and production. Augmented reality is currently a useful tool for presenting data to users and has promising development prospects in the future. Investments and the growing development of this sector make it more and more attractive on the market. There is potential to improve the quality of sensors used in AR, especially in terms of precision and cost (Paszkiewicz et al., 2019). Once hardware issues are overcome, smart AR glasses become a promising candidate as a daily-use tool in future smart factories (Horejsi et al., 2020). According to research, the use of VR enables the collection of data such as task completion time, distance traveled, and the identification of ergonomic hazards and system efficiency. Additionally, it allows you to observe many users performing the same tasks in laboratory conditions. Virtual reality shortens the time and costs of testing machine designs by simulating realistic operating conditions (Barkokebas et al., 2019). According to the literature, older generations are more confident about the future of AR/VR technologies and see greater benefits from their use. The industry is intensifying the implementation of these technologies (Noghabaei et al., 2020). In 2022, the study compared the training effectiveness of VR, AR, and actual equipment for maintenance tasks was conducted. For single-level maintenance tasks, the traditional training group had better training effects than the AR and VR groups. However, for multi-level maintenance tasks, the AR group had significantly better training effects than the VR group. The AR group also had higher training efficiency and lower cognitive load as the difficulty of maintenance tasks increased. Details can be found in (Liu et al., 2022). A comparative study (Joshi et al., 2021) was conducted between VR training and traditional video-based training, showing that VR training is more engaging and provides a better understanding of safety protocols and real-world experiences. Other researchers (Carretero et al., 2021) presented virtual tools to improve the creation of VR training for industry. The methodology focused on reconstructing workplaces in 3D, applying expected behavior to the 3D models, and delivering online training in a virtual environment. They will make the development of VR systems more efficient and cost-effective, enabling safe and productive operator training. Through the use of these virtual tools, it becomes possible to enhance the efficiency and affordability of developing VR systems, facilitating the training of operators in a productive and safe manner. Further researchers (Checa et al., 2022) emphasize that VR applications can provide a high rate of similarity to real training programs, filling the gap in traditional training and reducing unnecessary investment and economic losses. Many studies present the use of VR applications surpasses real teaching modules, offering a safe environment for testing systems without risk to operators (Andaluz et al., 2017). This opens the door to new VR applications that can significantly improve production and operator efficiency in industry.

The second area focuses on safety issues, both in the context of industry and training. Striving to improve safety practices, companies decide to use technologies that increase safety in industry, including risk assessment and training. The safety of employees and the environment is a key aspect here. Future research directions for a VR training system for the mining industry focus on analyzing the main components of the system as user, tasks, and software with databases (Zhang et al., 2017).

The third cluster is a set of technologies related to digital factory, digital manufacturing, digital twin and industrial process simulation. Research data from international companies and statistical organizations, such as PwC, IDC, Statista, clearly indicate the developing VR/AR industry and its shift in focus from the entertainment to the corporate sector. AR and VR technologies and appropriate tools are effective and useful in business process management, especially in the area of human resources and basic operational processes such as 3D visualization, production modeling, large-scale project management, automation and cybersecurity (Firu et al., 2020). Jiang's article (2012) details innovative method centers on using virtual reality technology to improve industrial production simulation systems.

As part of the work focused on "Animation Technology and Artificial Intelligence" cluster, developing research trends are presented, including technologies related to animation, the use of artificial intelligence and motion capture in various industrial fields. Advanced animation solutions and the use of AI to create more interactive and intelligent products are presented. Cluster 4 was created relatively recently and has the potential for dynamic development due to the continuous progress of technology in this field. The future trend is the integration of artificial intelligence and virtual reality, where both technologies complement each other. Therefore, it is necessary to further improve computer technology, especially the level of advancement of artificial intelligence systems, to increase the use of virtual simulation technology among employees (Yan, 2021).

Then, cluster 5 "Industry 4.0 and Smart Factories" focuses on industrial innovations, industrial development, especially the implementation of industry 4.0 technologies, smart factories and virtual factories. According to available literature, it includes technologies enabling the automation and monitoring of production processes, innovations in production and the use of data to create more intelligent and effective factories. VR digital tools cannot operate separately, so it is important to integrate them with other simulation tools and machine controllers to create a realistic virtual factory in real time. A virtual reality-based digital factory approach requires standardization of data formats and protocols, increased interoperability with digital tools and physical components, providing a deeper sense of immersion, and a more intuitive user interface (Chandra et al., 2021).

The “Education and Production Planning” cluster is focused on technologies related to education in the context of production, factory planning and virtual manufacturing. These technologies are aimed at effectively educating and preparing employees to work in modern production environments and planning production processes. The growing interest and increasing popularity of AR/VR in education and training emphas the need to explore new strategies for improving teaching processes using these technologies (Tan et al., 2022). Researchers (Paszkiewicz et al., 2021) have developed a methodology suitable for planning, managing, and implementing VR technology-based projects within Industry 4.0. The use of

VR in education aims to enhance the skills of future workers. With VR, designers, architects, and users can explore the space of future projects. It has been suggested that in the future, training coaches should be involved in the implementation phase, creating dedicated VR environments for training and documentation purposes. Moreover, in article (Bellalouna, 2020) was presented the VR application allows the user to be fully immersed in the virtual factory environment, which is a significant improvement over conventional 2D/3D tools that have limited planning area display capabilities and lack intuitive operational features. This innovative VR-based approach has the potential to improve the quality and efficiency of the factory planning process. As a next step indicated to widely implement this application in the digital factory process of industry partners to gain valuable user feedback and continue to improve the approach to factory planning using VR.

The last and smallest cluster is the "Science and Virtual Reality Environments" cluster, consisting of two elements: "immersive learning" and "virtual-reality environment". This is an area where advanced VR technologies are used to deepen knowledge and enable interactive learning. Recently, the increasing demand for reliable, secure, effective and cost-effective digital applications has prompted various industries to explore the potential of immersive technologies, especially Immersive Virtual Reality (IVR) (Radhakrishnan et al., 2021). According to the literature review (Roldán et al., 2019) the use of virtual reality technology can be used for more advanced learning and exploration of virtual environments. Comparing the utilization of virtual and augmented reality in the industrial context becomes a compelling topic when considering the future of immersive training systems. Ulmer et al. (2020) presented an innovative VR environment that uses gamification and adaptability to learn industrial scenarios. This environment dynamically adapts to each exercise by loading appropriate assets and making corrections based on CAD models. The visual guidance system gradually increases the difficulty of tasks, and KPIs allow you to assess user performance and create effective work sequences transferred to real applications.

5. Summary

Bibliometric analysis of scientific works on the use of VR technology in manufacturing processes leads to the conclusions, which can be used by practitioners and researchers interested in this topic.

Bibliometric analysis showed that the number of publications on this topic is constantly growing, which suggests a growing interest in VR in production management. Especially in the years 2016-2022, there is a rapid increase in interest among scientists in the analyzed direction. Increased interest in research on the use of VR in production and production processes, proves the growing role of this technology in industry. Over the last 3 years, there has been an increase in the number of scientific works devoted to the areas of education, immersive learning, training, digital factory, and artificial intelligence. Virtual reality can be used to train employees in a safe and interactive way. Research often focuses on training applications, which indicates the role of VR in improving employee competences and increasing safety. VR technology can open up new markets where enterprises can explore new areas of business. The trends reflect the drive to use VR as a tool for optimization, achieving industrial sustainability goals and shaping the future of manufacturing. Research into the use of VR technology can help enterprises optimize product design and production processes, which will save time and reduce costs. The study shows a clear trend related to interest in research and publications that combine virtual reality and artificial intelligence. This indicates that scientists are increasingly exploring the potential for synergies between these two areas. The combination of VR and AI technologies may be a promising tool for improving production processes and implementing innovations in industry. This is valuable information for both business managers and researchers interested in this field. The priorities activities in the future will be exploring how VR technology can be integrated with other advanced technologies such as artificial intelligence and the Internet of Things to further improvement manufacturing processes. An important aspect will also be conducting research on the use of VR for sustainable design of manufacturing processes and identifying ways to save raw materials, energy and minimize the impact on the environment.

The research results identified key and emerging seven areas that require further research and in-depth analysis. These areas are related to, among others sustainability, safety and training, artificial intelligence, Industry 4.0 and smart factories. Research in these areas may contribute to a better understanding of the role of VR in industry. As well as to develop more advanced solutions for the manufacturing industry. This work may encourage interdisciplinary research to fully understand the impact of VR on manufacturing. Research on the impact of VR in manufacturing is important both for the manufacturing industry itself and the broad field of VR technology.

The research limitations were related to using two most representative databases (Scopus and Web of Science) and choosing the scope of virtual reality technology with the manufacturing industry. In further work, the scope of the analysis can be extended to include works indexed in other databases (e.g. Elsevier, Emerald, EBSCO, Schematic Scholar).

The next research stages will be to further analyse mixed reality technology in terms of adaptation of techniques and technologies and digitalization of manufacturing enterprises.

Acknowledgements

This research was funded by a grant from the Ministry of Education and Science received by the Bialystok University of Technology, grant number WZ/WIZ-INZ/3/2022.

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