

Evolution and emerging trends of 4D printing: a bibliometric analysis

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Received: 3 May 2022 / Accepted: 17 September 2022

Abstract. The emergence of additive manufacturing technology opens up avenues for developing manufacturing industries, and a clear future direction for additive manufacturing is 4D printing. As a young field, it is full of new elements to be researched. In a summary and overview of the current state of research and trends, existing studies are generally manually reviewed and organized. It is susceptible to subjective thinking and knowledge blindness, making it difficult to reflect the current state of research in 4D printing in a comprehensive manner. This paper constructs a visualizing technology identification framework for the global 4D printing research field for manufacturing regarding basic information, technology evolution paths, knowledge structures, and emerging trends through bibliometric techniques and Gephi and CiteSpace software. The purpose of this paper was to provide a systematic, comprehensive, dynamic, quantitative, and objective analysis of the 4D printing research field in order to deepen and refine research in the field, as well as to reveal the overall existing knowledge structure and potential emerging trends. Researchers can use it to understand current research gaps and best practice pathways.

Keywords: 4D printing / additive manufacturing / bibliometrics / knowledge structures / emerging trends / evolution paths

1 Introduction

The manufacturing industry is the driving force for the growth, structural change, and acceleration of the economy, which exerts far-reaching and extensive influence on the national economy [1]. In particular, since the global coronavirus disease epidemic is gradually under control in 2022, the importance of the real economy has been reawakened, and the development trend and competitive landscape of the manufacturing industry are faced significant changes. Many countries with a renewed interest in manufacturing have high expectations for technological innovation and fusion. The concept of 4D printing represents the emerging direction of manufacturing, and it is also the paradigm of fusion of existing technology and innovation. The concept of 4D printing is derived from Tibbitts's presentation in 2013 at the earliest, referring to the new technology to fuse intelligent materials and additive manufacturing [2,3]. The 4D printing process is shown in Figure 1. No international consensus is reached over the definition of 4D printing. In a narrow sense, 4D printing is a production model in additive manufacturing,

which gives complexity of material geometry while transforming intelligent materials into products through three-dimensional printing [4–6]. In a broad sense, 4D printing serves as a comprehensive concept that systematically gives the shape, performance, and function of additive manufacturing components change over time under predetermined external stimulus [7].

4D printing is suitable for implementing an organization scheme of new methods, materials, and technologies in traditional additive manufacturing to cope with external environmental change, realize intelligence components [8]. It is a rapidly growing interdisciplinary field focusing on engineering, mathematics, materials, medicine, and chemistry. As the concept of 4D printing is introduced in the additive manufacturing industry, related scholars have considerably discussed and formed different research branches.

Scholars create a broad research framework around the fourth-dimensional concept of 4D printing and the stimulus-response model [9,10], and many branches of research have been expanded with the establishment of the framework. Around the design and analysis of intelligent components, based on his knowledge and experience, Janbaz [11] designs a self-folding and deformable component and demonstrates the most common forward design

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Fig. 1. The process of 4D printing.

method in the field of 4D printing. Faber [12] designs a bistable elastic self-folding bionic flying wing structure using the bionic design method, and it can be used as a classic example of inverse design. With the improvement of the intelligent components of one-way design, the two-way design gradually attracts attention. Mao [13] designs a reversible shape-changing component. Lee [14] analyses 143 papers from 1987–2017, reviews the reversibility research of 3D-printed shape-memory materials and proposes the new two-way 4D printing actuation method [15]. Around the molding processes and equipment, Gladman [16], inspired by the botanical systems, design composite hydrogel architecture and gel extrusion process. Ge [17] proposes a new 4D printing process based on high-resolution projection micro stereolithography and can create multi-material shape memory polymer architectures. Ma [18] creates a nickel-titanium shape memory alloy that uses selective laser melting to activate multiple shape recovery stages at different temperatures. Shi [8] finds that existing 4D printing methods are still dominated by traditional 3D printing processes and equipment. Around 4D printing of intelligent materials, scholars are summarized and innovative. Feng [2] summarizes and analyzes the printing methods, driving mechanisms, deformation methods, and applications for 4D printing of shape memory polymers and composites. Lu [19] points out that 4D printing of shape memory alloys is developing towards precise control of phase transition behavior and deformation controllable, and several considerations about 4D printing shape memory alloys are proposed based on unsolved problems. Liu [20] innovatively proposes elastic polymatrix nanocomposites and makes it possible to print ceramic structures in the field of 4D printing. Furthermore, Leng combs the development direction and challenges in memory polymer composites around the application development trends. The applications of shape memory polymer composites in 4D printing are discussed in detail, including building materials, textiles, aerospace, electronics, medical equipment, robots, information, daily necessities, and other fields [21–23].

Based on the development foundation of the intelligence materials and additive manufacturing industry in the past 30 years, 4D printing research has skyrocketed in the past eight years. It has developed a rich knowledge base and theoretical contributions that deserve to be summarized and refined in detail. However, most of the existing literature reviews on 4D printing remain at the level of interdisciplinary microscopic qualitative analysis of materials, processes, or engineering practices. The limited quantitative analysis also consists only of simple literature

counts and word frequency statistics. Moreover, these studies generally adopt artificial consultation and organization; in subjective summaries and generalizations of research status and trends, researchers can be easily influenced by subjective thought and knowledge blind zone. It is undeniable that these studies are essential for scholars to understand the current status of the 4D printing field. However, the scope and number of studies in the current literature review are pretty limited, comprehensively and objectively reflecting the overall situation of 4D printing studies is difficult. Therefore, an objective and accurate grasp of the history, current situation, and trends of 4D printing research is vital for understanding its development path, discovering new research problems to reference topic selection, academic innovation, and development trends in the field.

2 Research design

2.1 Research method and processing

This study adopted science mapping as the primary research method, and it is an image-displaying development course and structural relation of scientific knowledge using graphs as objects [24]. Based on existing theory and previous practice, this method was commonly used to interpret the discipline development trend [24], research progress, hotspot front [25], disciplinary knowledge structure [26], and dynamic evolutionary relationship [27]. Figure 2 shows the framework diagram of this study, and the main objectives are listed as follows.

Objective 1: This study presented a fundamental statistical analysis of the distribution of core journals, core authors, core countries, and disciplines in 4D printing to present the main picture of the field.

Objective 2: A keyword co-occurrence network analysis of the literature in this field was conducted to show the evolution of research themes.

Objective 3: This study provided an in-depth analysis of the knowledge structure of hotspot clustering based on the knowledge graph of literature co-citation and explored the emerging trends in the field of 4D printing through citation burst detection algorithms.

2.2 Source of data

Strict control over the literature selection process's scientific and comprehensive nature is necessary to achieve the research objectives properly. According to Bradford's

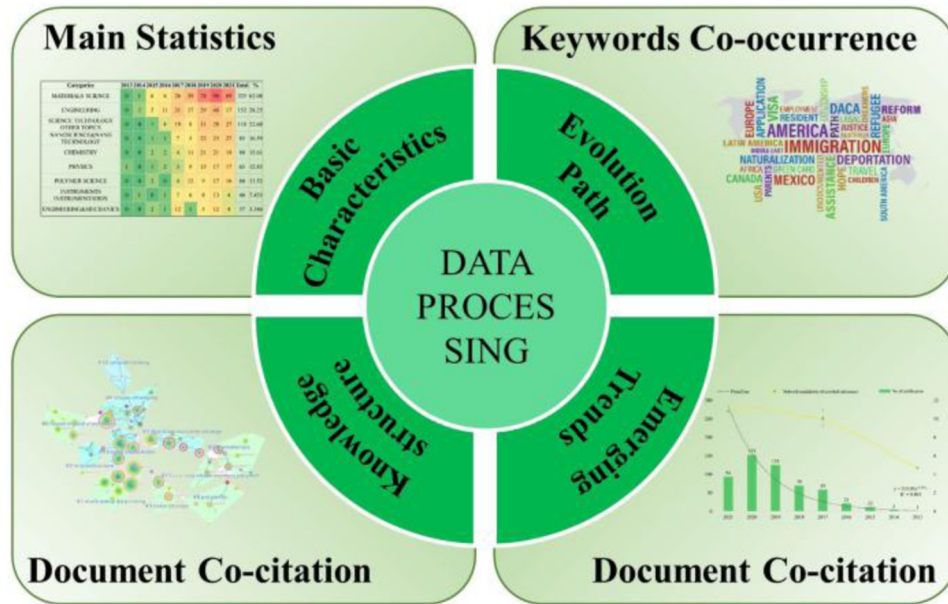


Fig. 2. Schematic of the thesis structure.

Literature Scattering Law, most critical pieces of literature are intensively included in core journals [28]. Therefore, all the literature in this study was obtained from SCI-EXPANDED, the core database of the Web of Science, which includes core academic journals with the greatest significant influence on engineering technology and natural sciences. This study carried out a duplicate check of the literature records. The authors filtered out a set of letters, news, notes, and proceeding papers that were less representative record types, and the final number of records was reduced to 533. The temporal parameters were set from January 1, 2013, to June 30, 2021. The Year per Slice was set at 1. The first 30% of high-frequency nodes each time were used. Table 1 displays additional search details.

3 Basic statistical analysis

Basic statistical analysis of 4D printing research literature mainly focused on a comprehensive analysis of research in this field regarding quantity and quality and a comprehensive understanding of relevant research scholars, regional research institutions, and countries.

3.1 Statistical analysis of core journals

Table 2 lists core journals of high co-citation and high publication volume in the field of 4D printing from January 1, 2013 to June 30, 2021. All impact factors were more significant than 2, and the average influence factor was greater than 8, indicating that high-quality research results have appeared in the 4D printing field in recent years. Different journals had different themes, emphasized different contents, and had different impacts. For instance, the Journal of *Advanced Materials* focuses on the frontiers

Table 1. Summary of searching for details.

Search setting	Content
Database	SCI-EXPANDED
Searching term	TS= (“4D print*”) OR TS= (“four-dimension print*”)
Literature	ARTICLE REVIEW
Time period	2013.1.1–2021.6.30
Searching time	2021/06/30
Results	584
Filter results	533

of materials science, particularly the chemical and physical properties of functional materials, with a preference for clearly interdisciplinary results. They are followed by the journal *Advanced Functional Materials* and *Acs Applied Materials & Interfaces*. The former focuses on reporting groundbreaking research in all aspects of materials science, emphasizing innovation in research results; the latter focuses explicitly on how newly-discovered materials and interfacial processes can be developed and used for specific applications. The journal *Materials & Design* is also a multi-disciplinary academic journal based on materials science and seeks to bring together engineering, physics, chemistry, and applications in technology. Unlike other academic journals, *Smart Materials and Structures* mainly explore the creation and utilization of novel forms of transduction. The results it publishes may be as disparate as the development of new materials and active composite systems, derived using theoretical predictions of complex structural systems, generating new capabilities by incorporating enabling new smart material transducers.

Table 2. List of cited journals and published journals.

Rank	List of Cited Journals			List of Published Journals		
	Count	Abbreviation	2020 Impact factor	Count	Abbreviation	2020 Impact factor
1	348	Adv. Mater.	27.39	39	ACS Appl. Mater. Interfaces	8.751
2	337	Sci. Rep.	3.998	28	Smart Mater. Struct.	3.613
3	292	Smart Mater. Struct.	3.613	22	Mater. Des.	6.289
4	289	ACS Appl. Mater. Interfaces	8.751	19	Adv. Funct. Mater.	16.836
5	282	Mater. Des.	6.289	15	Polymers	3.426
6	270	Adv. Funct. Mater.	16.836	12	Adv. Mater. Technol.	5.969
7	266	Nat. Mater.	38.663	11	Addit. Manuf.	7.002
8	228	Science	41.845	11	Virtual. Phys Prototy	7.312
9	219	Nature	42.778	10	Materials	3.057
10	214	Appl. Phys. Lett.	3.597	9	Adv. Mater.	27.39

3.2 Analysis of core author

It in this study, CiteSpace and Gephi software were used to analyze the relevant author networks. It also used dual indexes of the number of published articles and high co-citation frequency to more effectively mine the core academic groups and their members who have made outstanding contributions in the field.

The number of published articles is an index of the productivity of researchers in a field of research and an essential factor in promoting the rapid development of the field. The core authors and their academic team members with outstanding publication volumes are mined through the network of primary authors in Figure 3a. In Figure 3a, there exist many similar nodes spread out with a small number of nodes connected. This pattern indicated that studies regarding 4D printing are pretty dispersed. In addition, the association between researchers in academic exchange and scientific research was not close, and most researchers have carried out their studies in individual form or small group form. Therefore, no authoritative large-scale organizations have been formed. However, it should be pointed out that there are two prominent cooperative subnetworks.

Firstly, Qi was in a prominent position in the academic team from the Georgia Institute of Technology, and he ranked first with 30 published articles. Cooperative members include Dunn, Ge, Chao, Xiao, and others. They came from Singapore University of Technology and Design, Harvard University, Xi'an Jiaotong University, and other institutions. Qi and his collaborators are pioneers in elucidating the concept of the fourth dimension in 4D printing, proposing that time is the fourth dimension of the shape formation process, and in their demonstration, shape memory polymers are used in 4D printing to form a component whose shape changes through time [29]. The research of this team focuses on a variety of 4D printing methods, such as direct 4D printing method [30], inkjet printing method [31], hybrid printing method [32]. In addition, the team makes some research results on the nonlinear mechanics of soft materials, including various soft active materials commonly used for 4D printing, such as shape memory polymers [33], shape memory elastomeric composites [34], light-activated polymers [35], vitrimers [36]. These results provided a powerful reference for the research into 4D printing. They were followed by Leng from Harbin Institute of Technology, who published 27 papers, ranking second. Cooperative members include Liu, Zhang, Liu, and others. The research mainly focuses on direct ink writing based 4D printing [37], shape memory polymers based 4D Printing. The team uses 4D printing technology in a wide range of aerospace, aviation, and biomedical applications with excellent research results [21,38–40]. At the same time, the above two teams cooperated in the development and application of metamaterials and photopolymerization technology in the field of 4D printing.

High co-citation frequency is another index of the impact of researchers in a research field. Through the high co-citation network of authors in Figure 3b, some authors play a significant role in 4D printing, such as Tibbits, Ge,

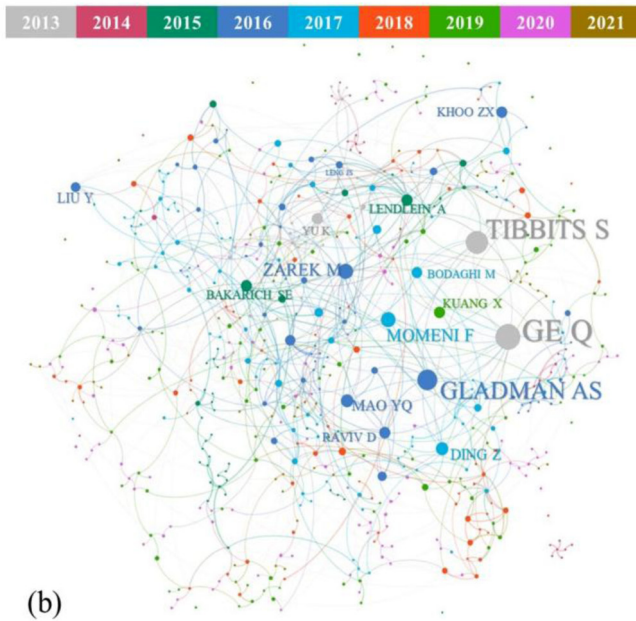
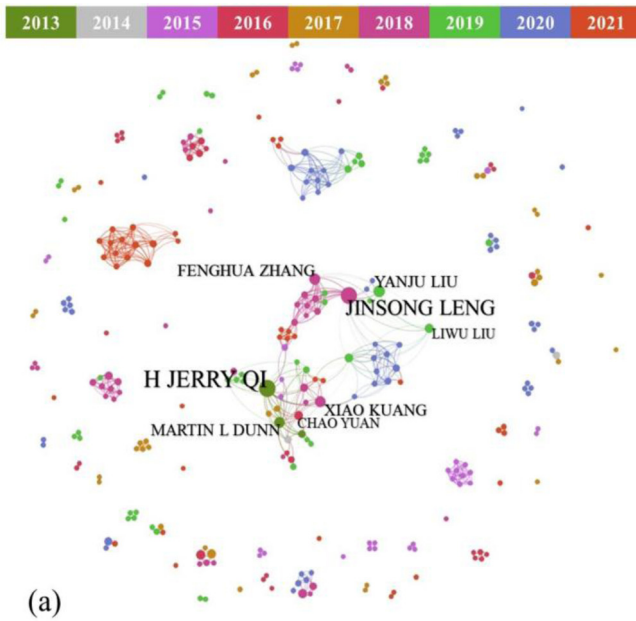


Fig. 3. (a) The network of main authors. (b) The network of main cited authors.

Gladman, and Zarek. Tibbits establish his Pioneering status in 4D printing research through his classical articles, *Active Printed Materials for Complex Self-Evolving Deformations* [41], *4D printing: multi-material shape change* [42], and *Large-Scale Rapid Liquid Printing* [43]. Chinese scholar Ge advances the research from multiple perspectives, such as influence factor, intelligent materials [29], 4D printing approach [17], structures [44,45], and constitutive model [46]. American scholar Gladman [16] concentrates on biomimetic research on 4D printing and further promotes the mechanics of biomimetic 4D printed structures [47]. Israeli scholar Zarek comprehensively



Fig. 4. Countries and institutions (Top 10).

advances the technical practice of 4D printing in flexible electronic devices [48], medical devices [49], and the fashion industry [50] through several articles. It was worth noting that the number of published articles was not necessarily related to the frequency of citations. For example, Qi and Leng ranked high in published articles and excelled in citation frequency. However, Tibbits only excelled in citation frequency.

3.3 Analysis of main countries and research institutes

The number of published articles reflects the level of research and the field's contribution to different countries, regions, and scientific institutions. The core areas where articles were published regarding 4D printing are distributed in North America, Europe, and Asia (Fig. 4). First, Asia topped the list with 329 published articles, accounting for 61.7% of the total number of published articles. The related studies in Asia were mainly concentrated in Southeast Asian countries, such as China, Singapore, Australia, South Korea, India, and Japan, where the Harbin Institute of Technology, the Nanyang Technological University, the Singapore University of Technology and Design, and Zhejiang University were important research institutions dedicated to studies on 4D printing. Followed by North America and Europe with 180 and 126 published articles ranked second and third, respectively, accounting for 33.7% and 23.6% of the total number of published articles. Related studies in North America and Europe were mainly concentrated in developed countries, such as America, England, France, Italy, and Germany, where the Georgia Institute of Technology, the French National Centre for Scientific Research, and Nottingham Trent University were important research institutions in the field of 4D printing. Chinese research institutions were ranked among the top in terms of the number of articles published and the number of citations. It indicated that international academics have gradually recognized the strength and influence of Chinese 4D printing research.

Categories	2013	2014	2015	2016	2017	2018	2019	2020	2021	Total	%
MATERIALS SCIENCE	0	1	6	8	26	39	78	98	69	325	62.08
ENGINEERING	0	2	5	11	31	17	29	40	17	152	28.25
SCIENCE TECHNOLOGY OTHER TOPICS	0	0	1	4	19	8	31	28	27	118	22.68
NANOSCIENCE&NANO TECHNOLOGY	0	0	1	1	7	5	22	23	27	85	16.59
CHEMISTRY	0	0	2	2	4	11	21	21	19	80	15.61
PHYSICS	1	0	1	2	3	9	15	17	17	65	12.83
POLYMER SCIENCE	0	0	2	0	4	12	9	17	16	60	11.52
INSTRUMENTS INSTRUMENTATION	0	1	0	1	7	6	8	13	4	40	7.435
ENGINEERING&MECHANICS	0	0	2	1	12	1	5	12	4	37	3.346

Fig. 5. Discipline distribution of 4D printing.

3.4 Analysis of discipline attributes

Figure 5 demonstrates the distribution of disciplines related to 4D printing over the last eight years. From left to right, the darker the red shade represented the higher volume of the published article in that discipline in that year, and the darker the green shade represented the lower volume of the published article in that discipline in that year. Research on 4D printing was focused on materials science, accounting for 62.08%, as it was one of the main pillars of research development in this field. It was followed by engineering science and science and technology, which generated 152 and 118 papers. In general, 4D printing presented an interdisciplinary trend, involving several fields of research, such as nanotechnology, chemistry, physics and mechanics. However, in terms of proportions, research and development in the main disciplines still dominated.

4 Analysis of technology evolution paths

This study tracked the dynamic change of studies on 4D printing based on Schneider's scientific discipline theory [51]. Schneider deems that a scientific field usually undergoes four development phases. A series of problems in the new fields are mainly confirmed in the first phase, belonging to the conceptualization phase. Through the development of tools and techniques, it is hoped that the questions obtained in the first phase will be studied; this phase belongs to the tool construction phase. As new technologies and tools continue to emerge to support research on existing problems, branches of research continue to emerge; this phase belongs to the application phase. Finally, the resulting theoretical and practical experience is organized and utilized; this phase belongs to the codification phase.

The keyword co-occurrence network is constructed based on co-occurrence analysis (counting the number of occurrences of every two words in the same literature group); its analysis allows for identifying relevant themes in the research field and finding dynamic evolution processes [52]. This study adopted a comprehensive map to explore the process of keyword association and knowledge evolution at the temporal level. In this research

field, 347 keywords surfaced from January 2013 to June 2021, and the total frequency of occurrence reached 2458. Figure 6 shows the high-frequency keywords that appeared more than five times in the 4D printing research field in different periods, presenting the technical evolution path of scholars focusing on research topics at different stages. In this coordinate system, the X-axis represented the time (year), and the Y-axis represented the frequency of keyword appearances. From top to bottom, the darker the red shade represented the higher frequency of the keyword, and the darker the green shade represented the lower frequency of the keyword. Currently, 4D printing research was in the transition period from phase two to phase three, with most studies focused on applying intelligence materials to additive manufacturing processes for the demonstration, study, and initial application of diverse shape change phenomena [29,53,54].

The first phase (2013–2014) was the conceptualization phase, based on the long accumulation of additive manufacturing technology and intelligent material technology, and the combination of the two then triggered the new research field, so this phase developed rapidly and produced a small amount of literature, mainly discussing the definition of 4D printing. For example, how to define the fourth dimension (such as the life axis or time axis) and how different response patterns (such as shape, performance, or function) followed the changes in the fourth dimension in response to different external stimuli. The 4D printing concept demonstration was another key problem in this phase [29], which has gradually introduced 4D printing into the tool construction phase by taking design and manufacturing as the entry point and modeling as the primary research method [44]. The research hotspots in this phase reflected a typical research trend, namely, starting from conceptual research of theoretical definition and settling on the design and verification of research methods.

In the second phase (2015–2018), the tool building phase, the increased amplitude of literature was enlarged, scholars attempted to explore some methods and techniques to realize the use of intelligence materials for additive manufacturing processes to achieve 4D printing technology. Scholars paid attention to the application of the additive manufacturing processes, researched fused deposition modeling [55], stereolithography [17], direct ink writing [56], and PolyJet as the primary printing methods. Meanwhile, it carried out extensive discussion of different printing methods within the framework of material properties and applications technology and extended to the research of composite materials [17]. Another group of scholars in this phase were dedicated to studying mechanical property [57], shape memory behavior [58], recovery force [59], and driving mechanisms [60] hinting that related scholar started to try to demonstrate and research diverse shape change phenomena. The above-mentioned hotspot evolution manifested that the 4D printing research was continuously refined, and they did not discuss extensive concepts such as 4D printing definition any longer. Multilevel and rich research topics were gradually proposed to transition to the third stage.

In the third stage (after 2018), the application stage, the ability to understand and solve problems has been greatly improved. The scale and distribution of the concentration

313	Stage I: Conceptualization		Stage II: Tool Construction				Stage III: Application		
					polymer				
					mechanical				
					property				
					technology				
					light	smart material			
					performance	tissue			
					polyurethane	nanocomposite			
					shape	soft			
					film	soft robotics			
					robust	metamaterial			
					shape memory	liquid crystal			
					alloy	elastomer			
					device	recovery force			
					elastomer	4dprinting			
					smart material	tissue engineering			
				shape	mechanics	shape memory			
				memory	behavior				
				network	deposition	self-folding			
			fabrication	stereolithogra	2 photon	soft actuator	photo		
				phy	polymerization		polymerization		
		4d printing	scaffold	biomaterial	alloy	3d/4d printing	driven		
		3d printing	3d	fused	3d bioprinting	bioprinting	release		
				deposition					
				modeling					
	shape memory	additive	hydrogel	drug delivery	biomedical	self-healing	pla		
	polymer	manufacturing			application				
	composite	behavior	actuator	system	sensor	niti	recovery		
	design	microstructure	actuation	direct ink	memory polymer	nanoparticle	shape-memory		
				writing			polymer		
	deformation	origami	gel	bone	complex	carbon nanotube	in vitro		
	topology	temperature	mechanism	active	delivery	bioink	shape memory		
	optimization			structure			effect		
	constitutive	model	4d	fdm	4d printing	parameter	soft robot	optimization	
	model				technology				
0	2013	2014	2015	2016	2017	2018	2019	2020	2021

Fig. 6. Technology evolution paths of 4D printing.

of technology in this field were modified because of the accumulation of advanced printing technology and material research and development in the second stage to facilitate the evolution of the 4D printing technology stage. In comparison with the second phase, the research perspectives of scholars experienced evident changes. Application topics, such as bioprinting [61], soft robotics [62], medical device [63], flexible electronics [64], and aerospace [40], attracted extensive attention. Such topics reflect the continuous development of technology, support the application of technology, and refine research branches. However, it should also be noted that this stage of research was still only at the stage of application to the phenomenon of shape change. As for realizing the application of performance change and functional change, there were very few reports, and no reliable and specific research ideas have been developed yet.

5 Analysis of knowledge structure

Co-citation analysis means that if two pieces of literature simultaneously appear in the bibliography from which the third literature is cited, then the two pieces of literature form a co-citation relationship. It reflects the main problems and methods as well as the main contributions

of academic article research. This analysis is a condensation of the main research opinions, and as an important indicator of literature cluster analysis, it reveals the structure of knowledge in a field, reflects influential scholars and classic literature [65]. Compared to the cutting-edge literature that constitutes the research hotspots and trends in a field and the current state of research, this section of the research focused on classic literature constitutes the knowledge base of a field.

The co-citation network for 4D printing included 169 nodes, 245 links, and 18 clusters. The researchers excluded non-essential clusters (including the small-scale and non-primary) and obtained 11 core clusters. Table 3 lists 146 nodes of the 11 clusters, accounting for 88% of the whole network. The Log-Likelihood Ratio (LLR) algorithm was used to name each cluster, and keyword phrase tags from the cluster articles were referenced [66]. The main clusters showed silhouette values between 0.8 and 1 in the 4D printing field, which indicated high homogeneity of clusters. Year expressed the average publishing year of each cluster.

Figure 7 shows the knowledge map of co-citation, where a link between two nodes means that the two documents are cited together, and the size of the node indicates the frequency of being cited. Colors were used to distinguish

Table 3. Summary of searching for details.

Cluster#	Size	Silhouette	Year	Label (LLR)
0	23	0.982	2013	Shape-changing
1	18	1	2016	Multi-metal 4d printing
2	16	0.895	2017	Biomaterials
3	13	0.95	2014	Spontaneous color change
4	12	0.958	2014	Highly stretchable
5	12	1	2014	Microstructure
6	12	0.937	2017	Liquid crystal elastomers
8	12	0.91	2017	Polymers
9	11	0.963	2017	Color change
10	10	0.986	2013	Smooth folding
11	10	1	2015	Two-way shape memory polymer

nodes and links at different times. This study used Modularity (Q) values and Mean Silhouette (MS) values to evaluate the clustering effect of knowledge maps. The value interval of Q is $[0,1]$. The higher the value of Q indicates that the better the cluster is obtained by the network, thus showing a more significant clustering structure. The clustering structure can be considered significant when $Q > 0.3$ and reasonable when $Q > 0.5$. The higher the MS value, the higher the clustering homogeneity, thus manifesting the greater consistency of the literature in the clusters. The clustering can be considered credible when $MS > 0.5$ and highly credible when $MS > 0.7$. The Q value of this network was 0.823, and the MS value was 0.931, meaning that the research network of 4D printing was of high credibility. Figure 7 also shows the citation burst of 4D printing literature. Red circles marked with citation bursts represented the most active fields of research, which allowed for precise tracking of disciplinary focus. According to the existing analysis, 4D printing was an academically underrated but widely radiated subject. Hence, this topic was worth further attention and in-depth discussion. Based on the above findings, this study further tracked the four active discipline orientations of the knowledge structure of the field, namely, four citation burst clusters 0, 2, 5, 8, and mined the classical literature in them, as shown in Figure 7. Tables 4–7 show high-frequency citations and four literature clusters (cited frequency derived from WOS, the search result on June 19, 2021).

The research topic of cluster 0 was shape-changing and focused on the mechanism, law, and stimulus-responsive mode of shape-changing (Tab. 4). Cluster 0 included 23 pieces of literature. Hence, it was the largest cluster, and the average citation time was the same as the 4D printing concept proposal time in 2013, so this cluster represented the basis of 4D printing research. The research foundation of shape-changing has derived from the development of material technology and shape memory effect research. Meanwhile, this cluster has become a discipline orientation with the fastest development, the most active technical research, and the most significant attention to 4D printing. At present, shape-changing studies were divided into retrospective and quantitative studies, mainly research articles. Wan reviews the shape memory effect, progress in

shape memory enabling mechanisms and triggering methods, variations in shape memory forms (shape memory surfaces, hydrogels, and microparticles), shape memory behavior (one-way and two-way), and novel fabrication methods; his article is cited very frequently [67]. Sun summarizes the concepts, types, and applications of stimulated responses of shape memory alloys and shape memory polymers in engineering [68]. Liu discusses the shape recovery effect and introduces a general mechanism in the shape memory polymers and their composites through the comparative study method while reviewing the applications of shape memory polymers and shape memory polymer composites reinforced with fiber materials in the aerospace field [69]. The other type was application-oriented quantitative studies, which reaches shape-changing goals mainly through design and theoretical model innovation. Gladman's works are publications with the highest cited frequency in this cluster. He provided the complete quantitative description of the printed composite hydrogel architectures and their shape-changing properties so far, and related research may lay a foundation for the later 4D bioprinting [16]. Felton develops shape-memory composites that fold themselves along embedded hinges and use these composites to recreate fundamental folded patterns derived from computational origami that can be extrapolated to a wide range of geometries and mechanisms [70]. In summary, research in shape change has been carried out in two main ways: one was to explore stimulated deformation laws of single intelligent materials and then apply them directly; another was to code composite components and structures to form predetermined deformation laws then apply them. Although scholars have enriched the relevant research under this cluster from different perspectives, the vast majority of studies are still only at the stage of phenomenal demonstration of shape change, and very little has been reported on how to achieve performance change and functional change. No reliable and specific research ideas have been formed. It also has hindered the practice and application of 4D printing, not to mention the exploration of systematization and industrialization.

The research topic of cluster 2 was biomaterials and focused on the biocompatible materials developed under this cluster incorporating natural components that have

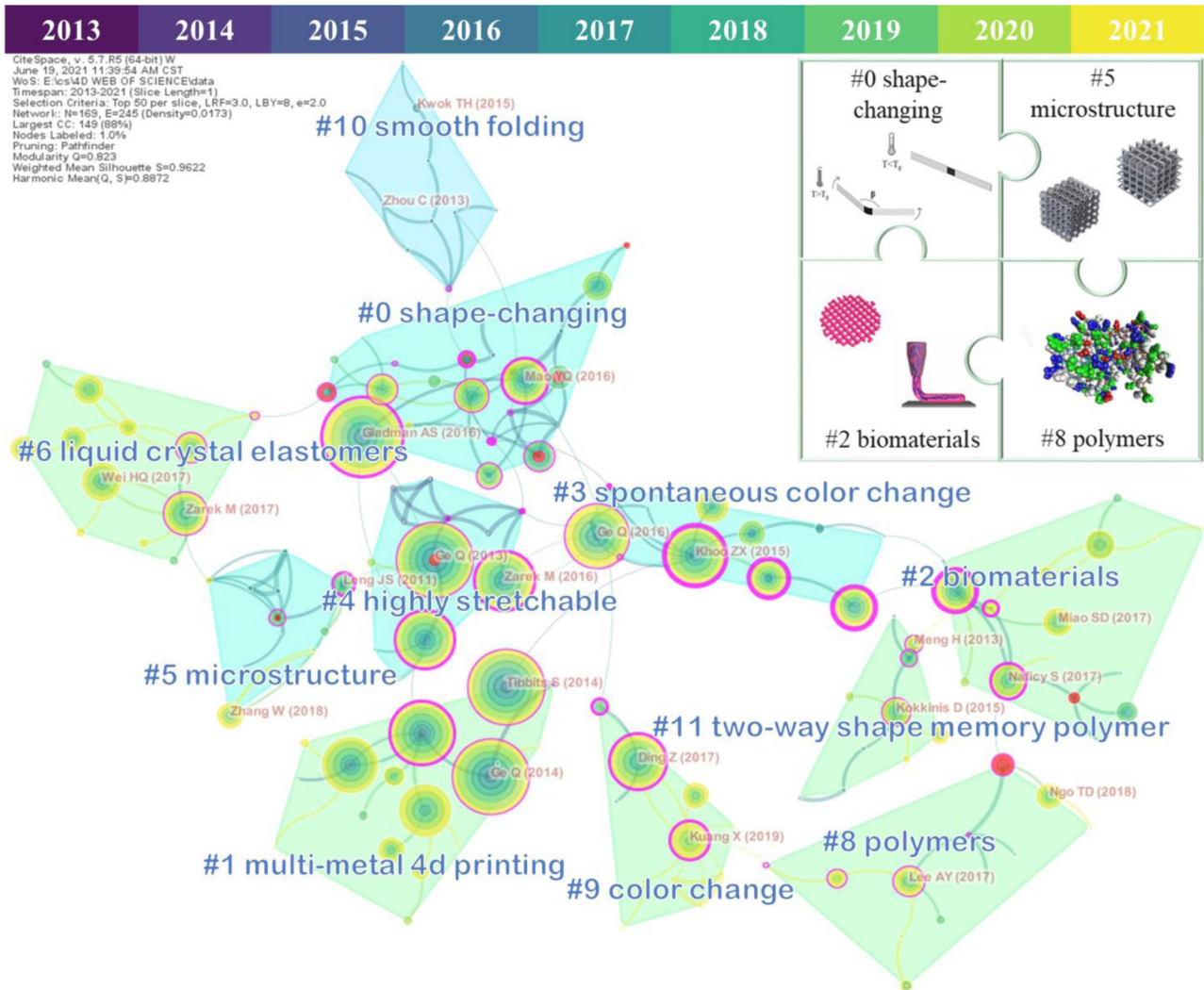


Fig. 7. Co-citation cited knowledge maps and active discipline orientations of knowledge structures.

Table 4. Cited references and citing articles of cluster 0 on shape-changing (top 5).

	Cited references	Cited articles
Cites	Author (Year) Journal, Volume, Page	Author (Year) Title
1163	Gladman [16] (2016) NAT MATER, 15, 413	Kuang (2019) Advances in 4d printing: materials and applications [91].
692	Wan [67] (2013) POLYMERS, 5, 1169–1202	Rastogi (2019) Breakthrough in the printing tactics for stimuli-responsive materials: 4d printing [92].
619	Sun [68] (2012) MATER DESIGN, 33, 577–640	Wan (2020) Direct ink writing based 4d printing of materials and their applications [37].
537	Felton [70] (2014) SCIENCE, 345, 644–646	Garces (2021) Advances in additive manufacturing of shape memory polymer composites [93].
490	Liu [69] (2014) SMART MATER STRUCT, 23, 2	Falahati (2020) Smart polymers and nanocomposites for 3d and 4d printing [94].

Table 5. Cited references and citing articles of cluster 2 on biomaterials (top 5).

	Cited references	Cited articles
Cites	Author (Year) Journal, Volume, Page	Author (Year) Title
177	Duigou [55] (2016) MATER DESIGN, 96, 106–114	Rastogi (2019) Breakthrough in the printing tactics for stimuli-responsive materials: 4d printing [92].
148	Miao [71] (2016) SCI REP-UK, 6, 27226	Garces (2021) Advances in additive manufacturing of shape memory polymer composites [93].
119	Miao [60] (2017) MATER TODAY, 20, 577–591	Miao (2017) 4d printing of polymeric materials for tissue and organ regeneration [60].
101	Naficy [72] (2017) MACROMOL MATER ENG, 302, 1600212	Lee (2017) Two-way 4d printing: a review on the reversibility of 3d-printed shape memory materials [15].
83	Bodaghi [73] (2019) MATERIALS, 12, 26–36	Chung (2017) Effective software solutions for 4d printing: a review and proposal [95].

Table 6. Cited references and citing articles of cluster 5 on microstructure (top 5).

	Cited references	Cited articles
Cites	Author (Year) Journal, Volume, Page	Author (Year) Title
1163	Murphy [74] (2014) NAT BIOTECHNOL, 32, 773–785	Kuang (2019) Advances in 4d printing: materials and applications [91].
692	Leng [78] (2011) PROG MATER SCI, 56, 1077–1135	Rastogi (2019) Breakthrough in the printing tactics for stimuli-responsive materials: 4d printing [92].
619	Hu [77] (2012) PROG POLYM SCI, 37, 1720–1763	Wan (2020) Direct ink writing based 4d printing of materials and their applications [37].
537	Compton [76] (2014) ADV MATER, 26, 5930	Garces (2021) Advances in additive manufacturing of shape memory polymer composites [93].
490	Inzana [75] (2014) BIOMATERIALS, 35, 4026–4034	Falahati (2020) Smart polymers and nanocomposites for 3d and 4d printing [94].

achieved a wide range of applications in the medical field (Tab. 5). Regarding the research articles with the highest cited frequency in this cluster, Duigou proposes that hygromorphic biocomposites represent a novel use of natural fibers to produce original self-bending devices that actuate in a moisture gradient, and this makes the fused deposition modeling of hygroscopic biocomposites enables a shift towards 4D printing [55]. In the form of a literature review, Miao explores and discusses the applications of 4D printing in tissue and organ regeneration, such as developing synthetic tissues and implantable scaffolds [60]. Afterward, Miao solidifies a novel renewable soybean oil epoxidized acrylate, using a 4D laser printing technique into innovative and highly biocompatible scaffolds capable of supporting multipotent human bone marrow growth mesenchymal stem cells [71]. These studies have advanced the fusion of biomaterials and 4D printing technology into

application fields from theory to practice. Naficy presents a series of hydrogel-based inks developed to print 3D structures capable of reversible shape deformation in response to hydration and temperature. The author also provides a simple model to predict their bending characteristics, including the bending curvature and bending angle [72]. Bodaghi shows how fused deposition modeling as a three-dimensional printing technology could engineer adaptive metamaterials with performance-driven functionality built directly into materials. It can be called functionally graded 4D printing because the structure is fabricated additively and programmed functionally. Experiments show that 4D printed metamaterials have great potential in mechanical and biomedical applications like structural and dynamical switches, self-tightening surgical sutures, and self-coiling and deploying stents [73]. Through the abovementioned literature, biomaterials have

Table 7. Cited references and citing articles of cluster 8 on polymers (top 5)

	Cited references	Cited articles
Cites	Author (Year) Journal, Volume, Page	Author (Year) Title
177	Ngo [80] (2018) COMPOS PART B-ENG, 143, 172–196	Garces (2021) Advances in additive manufacturing of shape memory polymer composites [93].
148	Wang [82] (2017) COMPOS PART B-ENG, 110, 442–458	Kuang (2019) Advances in 4d printing: materials and applications [91].
119	Ligon [83] (2017) CHEM REV, 117, 10212–10290	Rastogi (2019) Breakthrough in the printing tactics for stimuli-responsive materials: 4d printing [92].
101	Hager [81] (2015) PROG POLYM SCI, 49–50, 3–33	Zhang (2019) Magnetic programming of 4d printed shape memory composite structures [96].
83	Lee [15] (2017) ENGINEERING-PRC, 3, 663–674	Miao (2017) 4d printing of polymeric materials for tissue and organ regeneration [60].

become a non-negligible focus of attention in tissue engineering, regenerative medicine, mechanical and biomedical applications. As reflected in the analysis of the cited articles, scholars were now emphasizing hydrogels because they are one of the most viable biomaterials for 4D printing, and this cluster has been multiplying as a refinement research cluster. Given this, future research in this field will focus on response structure design-based hydrogels and the development of advanced hydrogel-based biomaterial inks.

The research topic of cluster 5 was microstructure and focused on the following main research directions: improvement of biomaterial properties (mainly biocompatibility) and shape memory polymer properties (mainly shape memory effects) through microstructural exploration (Tab. 6). Murphy's review of 159 articles from 1991 to 2013 proposes that bioprinting microstructures involve additional complexity (such as choice of materials, cell types, cell growth, and differentiation factors) and technical challenges related to the sensitivity of living cells to microstructures compared to non-bioprinting. Furthermore, Murphy also summarizes examples of bioprinting microstructure that have been used for the generation and transplantation of several tissues [74]. The latest article with highly cited frequency was the research conducted by Inzana. Inzana seeks to improve the 3D printed calcium phosphate scaffolds from the microstructure design parameters field, aiming to ensure maximal biocompatibility and osteoconductivity with sufficient mechanical properties [75]. Compton shows the influence of controlled microstructure on strength values by novel epoxy-based inks [76]. Based on the clustering results analysis, another part of the literature represents attention paid by scholars to shape memory polymers. The literature review on shape-memory polymers and their derivatives by Hu and Leng provides a valuable theoretical foundation for subsequent further studies. Hu reviews the research results of shape memory polymers and their derivatives, primarily the microstructures of composites and their current applications [77]. Leng review that shape memory polymers, especially shape memory polymer

composites, can be developed by microstructural changes into multifunctional materials actuated by various methods, such as thermal-induced, electro-activated, light-induced, magnetic-actuated, and solution-responsive shape memory polymers [78]. Liu studies microstructural design for enhanced shape memory behavior of 4D printed composites based on carbon nanotube and polylactic acid filament, and this also serves as a practical application and extension of theoretical research in another field of clusters [79].

The research topic of cluster 8 was polymers, and the average citation was the latest, representing one of the cutting-edge fields of 4D printing research and one of the main pillars driving the development of 4D printing technology at this phase (Tab. 7). The emergence of 4D printing technology has solved the problem that shape memory polymers can only produce simple deformable structures under traditional manufacturing processes. It takes the design, preparation, and functionalization of shape memory polymers to develop a new and more intelligent direction. Ngo presented the current status of the development of polymers and their composites while providing a comprehensive review of additive manufacturing techniques, applications, and materials [80]. Hager further focuses on shape memory polymers, briefly summarizing the history of shape memory polymers and their current development and concept [81]. In addition, future developments in the field are discussed. Because of the intrinsically limited mechanical properties and functionalities of printed pure polymer parts, Wang provides an in-depth analysis of the 3D printing of polymer materials and the performance of composite 3D printed parts [82]. The formation methodology and the performance of particle-, fiber- and nanomaterial-reinforced polymer composites are emphasized, essential limitations are identified to motivate the usability of printing polymer composite materials. Ligon focuses on polymer processing and the development of polymers and advanced polymer systems specifically for additive manufacturing. He demonstrates that polymer-based additive manufacturing plays a crucial role in the emerging additive manufacturing

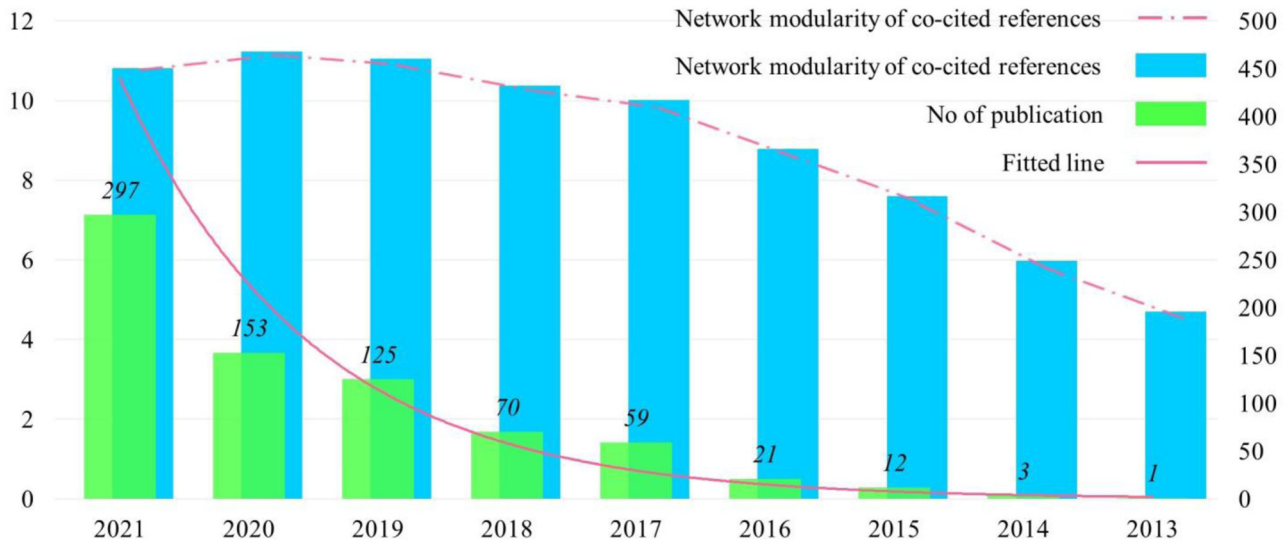


Fig. 8. Number of publications and the modularity of the network.

of advanced multifunctional and multi-material systems, including living biological systems and life-like synthetic systems [83]. Current studies have extended the application practice of polymers in the field of 4D printing, such as scholars have researched two-way 4D printing [15], dynamic jewelry and fashionwear [50], and nylon fabric 4D printing [84]. However, the raw materials used for 4D printing shape memory polymers are still relatively homogeneous, and there are many programmable materials with excellent properties and functions that are yet to be applied to 4D printing.

6 Emerging trends

Discovering and mining the groundbreaking changes and emerging trends in a research field helps keep track of the latest developments in that field of study [85]. By tracking changes in network modularity, new trends in 4D printing research can be captured. The knowledge structure of 4D printing can be expressed as a literature co-citation network, and recent articles may result in profound structural changes of this network. Figure 8 shows the summary of articles published in 4D printing research from 2013 to 2021. Overall, the total number of articles published in the field has increased each year and showed an exponential growth trend. The red line represented the fitted curve of the number of articles published per year, and with the following formula:

$$y = 518.05e^{-0.598x}$$

$$R^2 = 0.863$$

where y was the number of published articles per year and x was the year. The R^2 value was 0.863, indicating an acceptable fit, meaning that the 4D printing research has maintained a rapid growth trend in the next few years. The green bar marked the total number of articles issued in historical years. The number of published articles was

growing slowly before 2017. Since 2017, the number of published articles started increasing by a significant margin year by year, meaning that 4D printing research has gradually become a research hotspot and has attracted increasing attention from scholars. The red dashed line and blue bar showed a modularity change across the network, which presented an overall upward trend. However, with 2017 as the cut-off point, the average growth rate was 51.87% before 2017; it rapidly declined to 5.71% after 2017. The abovementioned evidence showed that research on 4D printing experienced some significant structural changes in 2017. As a calculation technique used to discover events and other mutation types [86], the results of citation burst detection techniques can effectively determine changes in research novel trends caused by changes in a short period. The researchers conducted an in-depth survey of the published literature around 2017 by citation burst detection techniques.

Through a comprehensive analysis of articles published, the high growth rate of network modularization was manifested by the rapid division of previous clusters in 2017. Table 8 lists 11 literature belonging to the five clusters that had citation bursts before 2017. The pioneering research by Felton [70] in the aspect of self-folding had the highest citation burst, which reached as high as 9.29, and the research lasted from 2016 to 2018. In addition, Liu's [87] article about self-folding started having citation bursts in the same time period, which reached as high as 8.25. This value was accurate because the research on deformation in 4D printing revolved around material properties and material stimulus-response properties; these two articles provided paradigmatic research on deformation mechanisms and applications from the two aforementioned directions, which led to their high citation burst rates. Murphy [74] reviews examples of bioprinting microstructure that have been used for the generation and transplantation of several tissues; that was precisely why his citation bursts continued from 2016 to 2019 and drove subsequent research for the microstructural design.

Table 8. Articles published with citation bursts.

Reference	Title	Strength	Duration	Cluster#
Ge, 2013	Active materials by four-dimension printing [29].	3.44	2014–2016	4
Zhou, 2013	Digital material fabrication using mask-image-projection-based stereolithography [88].	5.9	2015–2017	10
Tibbits, 2012	4D printing: multi-material shape change [42].	4.04	2015–2016	4
Felton, 2014	A method for building self-folding machines [70].	9.29	2016–2018	0
Liu, 2012	Self-folding of polymer sheets using local light absorption [87].	8.25	2016–2018	0
Yu, 2015	Controlled Sequential Shape Changing Components by 3D Printing of Shape Memory Polymer Multilaterals [97].	6.26	2016–2017	0
Ryu, 2012	Photo-origami-bending and folding polymers with light [98].	5.36	2016–2017	0
Yu, 2014	Reduced time as a unified parameter determining fixity and free recovery of shape memory polymers [33].	5.36	2016–2017	0
Chua, 2015	3D Printing and Additive Manufacturing: Principles and Applications (5th Edition) [99].	4.59	2016–2017	3
Wu, 2016	Multi-shape active composites by 3D printing of digital shape memory polymers [100].	4.22	2016–2017	0
Murphy, 2014	3D bioprinting of tissues and organs [74].	2.34	2016–2017	5
2017				
Xie, 2010,	Tunable polymer multi-shape memory effect [89].	7.5	2017–2018	14
Teoh, 2017,	Hierarchically self-morphing structure through 4D printing [90].	6.92	2017–2018	2
Liu, 2014,	Shape memory polymers and their composites in aerospace applications: a review [69].	5.18	2017–2018	0
Zarek, 2016,	4D printing shape memory polymers for dynamic jewelry and fashionwear [50].	3.91	2018–2019	8

Zhou [88] from the printing process cluster presents a novel and pioneering approach towards digital material fabrication based on the stereolithography process, expanded research on printing methods and principles. The above observations can be shown that the growth rate of modularity of the whole network was higher before 2017, as the research centered on 4D printing showed a divergent trend. The rate of network modularity declined sharply after 2017, meaning that network clusters presented a centralized tendency. Table 8 lists four literature with citation bursts, and the new cluster is reduced to 3. This number indicated that more and more scholars focused on geometry-driven finite elements, biomaterials, and polymers, thus influencing the modularity of the whole network. At the molecular level, Xie [89] from the geometry-driven finite elements cluster creatively proposes

that the maximum number of temporary shapes a shape memory polymer can memorize correlates directly to the number of discrete reversible phase transitions (shape memory transitions) in the polymer; triggered subsequent research in the field. Teoh [90] from the biomaterials cluster brings forward a hierarchically self-morphing bionic structure through 4D printing to achieve predefined global and local shape changes. Zarek from the polymers cluster uses a methacrylate semi-crystalline polymer to print objects exhibiting thermally triggered shape memory behavior. This polymer is utilized for demonstrating the fabrication of dynamic jewelry and a shoe accessory by digital light processing printing [50]. It has largely enriched the application of polymer materials in 4D printing. The three citation bursts lasted until 2018–2019, exerting the most significant effect on the research fronts of 4D printing.

7 Conclusion

7.1 Main research conclusions

This study adopted the scientific bibliometric method to summarize the characteristics and basic information in 4D printing research with scientific mapping, based on which its evolution was depicted, and its future development direction was explored. In addition, this study analyzed the core journals, core authors, core countries, subject distribution, keyword co-occurrence, and literature co-citation knowledge maps of 533 articles in the field of 4D printing from January 2013 to June 2021 using CiteSpace and Gephi. The results are as follows:

High-quality research results are generated in this field. The most frequently cited and high publication volume core journals are mostly materials science research, which has apparent scientific intersectionality. Except for the close cooperation among academic teams represented by Qi and Leng, the scholarly communication among the remaining core authors is not close, and no large-scale authority has been formed. As prominent high-citation authors, Tibbits, Ge, Gladman, Zarek, Qi, exert enormous influence on 4D printing research. The main research areas and research institutions are distributed in North America, Europe, and Asia. This field centers on materials science and engineering with increasingly evident interdisciplinary fusion attributes and pluralistic development trends.

Under the framework of the four-stage theory of disciplinary development, 4D printing research is rapidly developing based on the mature research foundation in additive manufacturing, following the technological evolution path of concept definition, tool construction, and application stages. According to the results of keyword co-occurrence, research on 4D printing is in the transition period from the second phase to the third phase. The research themes have stayed at the material level over the last eight years, focusing primarily on various printing techniques under various material properties and application technologies and extending to the research of composite materials. Discussing the mechanical characteristics, shape memory behavior, resilience, and driving mechanisms of the material from the application field is another focus of the research theme. According to keyword co-occurrence results, the research perspectives of scholars have gradually changed, the research hotspots of the technological application of 4D printing have gradually emerged. This change reflects the contemporary, cutting-edge, and evolving character of the research topic.

Based on the literature co-citation results, the research results related to 4D printing can be subdivided into 11 mainstream research fields. Four of these clusters (including shape-changing, biomaterials, microstructure, and polymers) also represented four active discipline orientations of the knowledge structure of the field, which have attracted the attention of many scholars in recent periods. Through further mining the classical literature in them, the development trajectory of core fields related to 4D printing was identified, thus laying a solid foundation for exploring emerging development directions.

The volume of literature in the field of 4D printing research has grown exponentially. With 2017 as the cut-off point, the modularity rate is changed due to reducing research fields. Clusters were reduced from 5 to 3; it is the main reason for the sharp drop in the modularity rate after 2017. On the grounds of citation burst intensity and duration, biomaterials, geometry-driven finite elements, and polymers may become emerging trends in the field of the research of 4D printing.

The comprehensive framework of this study offers valuable insights to researchers and practitioners to better understand 4D printing research and can also serve as a paradigm for the study of multidisciplinary problems. For governmental officials, stakeholders, and entrepreneurs, this study provides references for formulating industrial development guidance and policies. For manufacturing practitioners, this study reveals the existing integral knowledge structure and potential emerging trends for practice, which practitioners can draw from our analysis to understand current research gaps and best practice pathways.

7.2 Expectations and limitations

Although research in the field of 4D printing has made outstanding progress, most of it is still dominated by basic research. However, the ultimate goal of new technology is frequently industrial operation. As a result, new technological research and development should take root in today's complex industrial operation. The transition from "technical recognition and parsing" to "industrial recognition and parsing" should be realized. In the foreseeable future, the research and development direction will gradually change to achieve technological application targets. To meet the new trends and goals of applying 4D printing technology, the medical, construction, aerospace, and commercial fields will be investigated. As a product of technological fusion and innovation, 4D printing may be influenced by emerging technologies (such as big data, cloud computing, the internet of things, artificial intelligence, robotics, and virtual reality).

However, there are some shortcomings in our study. For example, although the Web of Science core collection is chosen as the data source, the authors acknowledge that some important research publications on 4D printing may have been missed (e.g., Ph.D. theses and patents). It is worth noting that the number of articles in the studied collection was published before June 30, 2021, so future changes and developments are still possible.

Conflicts of interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Acknowledgements. This research was supported by the National Natural Science Foundation of China [grant number 52175019], Natural Science Foundation of Beijing Municipality [grant number 3212009].

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Cite this article as: Wencai Zhang, Zhenghao Ge, Duanling Li, Evolution and emerging trends of 4D printing: a bibliometric analysis, *Manufacturing Rev.* **9**, 30 (2022)