

Visualizing the Hotspots and Emerging Trends of 3D Printing through Scientometrics

Abstract

Purpose - 3D printing is believed to be driving the third industrial revolution. A comprehensive understanding of the hotspots and trends of 3D printing may promote the theory development of 3D printing, help researchers to determine the research direction, and provide a reference for enterprises and government to plan the development of 3D printing industry. However, a scientometric visualizing of 3D printing research and an exploration its hotspots and emerging trends are lacking. Therefore, it was necessary to carry out this relevant research.

Design/methodology/approach – Based on the theory of scientometrics, 2769 literatures on the 3D printing theme were found in the Web of Science Core Collection' SCI indexes between 1995-2016. These were analyzed to explore the research hotspots and emerging trends of 3D printing with the software CiteSpaceIII.

Findings – (1) hotspots appeared first in 1993, grow rapidly from 2005, and peaked in 2013; (2) hotspots in the "medical field" appeared earliest and have remained extremely active; (3) hotspots have evolved from "drug", "printer", "rapid prototyping" and "3D printing" in the 1990s, through "laser-induced consolidation", "scaffolds", "sintering" and "metal matrix composites" in the 2000s, to the current hotspots of "stereolithography", "laser additive manufacturing", "medical images", etc.; (4) "3D bioprinting", "titanium", "stem cell" and "chemical reaction" were the emerging hotspots in recent years; (5) "commercial operation" and "fusion with emerging technology such as big data" may create future hotspots.

Research limitations/implications - It is hard to avoid the possibility of missing important research results on 3D printing. The relevant records could be missing if the query phrases for topic search do not appear in records. Besides, in order to improve the quality of data, this study selected articles and reviews as the research objects, which may also omit some records.

Originality/value - First, this is the first paper visualizing the hotspots and emerging trends of 3D printing using scientometric tools. Second, not only "burst reference" and "burst keywords", but also "cluster" and "landmark article" are also selected as the evaluation factors to judge the hotspots and trends of a domain comprehensively. Third, overall perspective of hotspots and trends of 3D printing is put forward for the first time.

Keywords - 3D printing, Additive manufacturing, Rapid prototyping, Scientometrics, CiteSpace, Visualization, Research hotspots, Emerging trends

Paper type – research article

1. Introduction

3D printing is changing the world. It is believed by some to be driving a new industrial revolution ([Economist, 2012](#)). American Time magazine has listed 3D printing as one of the top ten fastest-growing industries ([Lipson and Kurman, 2013](#)). 3D printing could play a significant part in future economic growth, and is considered to be a disruptive technique according to the disruption pattern ([Christensen, 2013](#)). Therefore, 3D printing has been widely investigated by many governments, research institutions, enterprises and media ([Ratto and Ree, 2012](#); [Wang and Su, 2015](#)). In developed countries, particularly in the United States, 3D printing has been in widespread use for a long time ([Klein et al., 2013](#)). Some developing countries have also begun to focus on this technology. For example, China as the largest developing country incorporated 3D printing into its 863 plan ([Jin and Ji, 2013](#)), and the 3D printing industry has achieved rapid development in recent years.

3D printing is a process of joining materials to make objects from 3D model data, usually layer by layer ([ASTMInternational, 2012](#)). Contrary to traditional subtractive manufacturing, 3D printing is a material addition technology capable of creating complex shapes similar to casting, forming and injection moulding ([R. I. Campbell et al., 2012](#)). 3D printing has the characteristics of fast set-up and geometric freedom ([Lipson and Kurman, 2013](#)). Compared to traditional manufacturing technology, it is simpler, sometimes cheaper, and often more convenient to use ([T. Campbell et al., 2011](#)). In particular, 3D printing technology can produce an assembly with complex structures in a single-step process ([Chua and Leong, 2004](#)). It also helps the environment through the flexibility that allows manufacturers to optimize designs for lightweighting and lean production ([Karjalainen et al., 2007](#)) so as to reduce the use of resources ([Chu et al., 2008](#)). More than 100 kinds of raw materials can be used with 3D printing, such as hot plastic, metal, nylon, acrylic, gypsum, metal alloys, ceramics, wax, sand, stone, paper, rubber, edible materials and so on ([Bassoli et al., 2007](#); [Kneissl, 2013](#)). Depending on the material and machine technology used, 3D printing (Additive Manufacturing) has been classified into 7 categories, namely VAT Photopolymerisation, Material Jetting, Binder Jetting, Material Extrusion and Powder Bed Fusion ([ASTMInternational, 2012](#)). 3D printing has been applied in a variety of industries, such as aerospace ([T. Campbell et al., 2011](#); [Lee et al., 2016](#)), automotive ([Guo and Leu, 2013](#); [Rahim and Maidin, 2014](#)), biomedical ([Gebhardt et al., 2010](#); [Hutmacher, 2015](#); [Marga et al., 2012](#); [Melchels et al., 2012](#)), building and construction ([Perkins and Skitmore, 2015](#); [Song and Hu, 2015](#); [Valkenaers et al., 2014](#)), marine and offshore ([Bhudolia et al., 2015](#); [Chua et al., 2016](#); [Tham et al., 2015](#)), food industry ([Lipton et al., 2015](#); [Sun, Peng, et al., 2015](#); [Sun, Zhou, et al., 2015](#)),

environmental engineering ([Bara et al., 2013](#); [Cho et al., 2015](#); [Mathai, 2015](#)), as well as desalination and water treatment ([Andersson et al., 1985](#); [Johnson et al., 1993](#)).

The related academic studies on 3D printing are rapidly increasing ([Bhasin and Bodla, 2014](#)). An investigation conducted by the authors showed the annual number of published and cited papers retrieved by a topic search on the Web of Science has grown rapidly in recent years, as shown in Figure 1 and Figure 2.

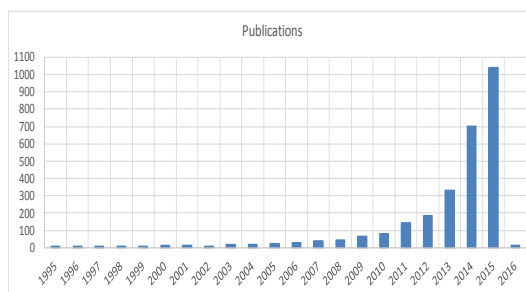


Figure 1 Published articles each year

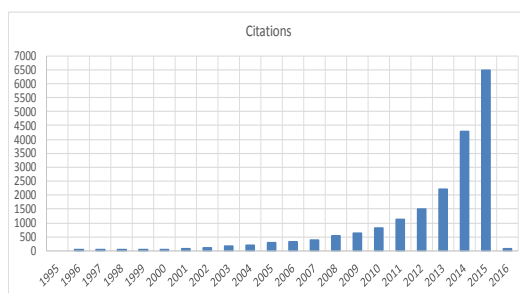


Figure 2 Cited times of the articles each year

The research topics around 3D printing are also varied. Figure 3, called a Foam Tree shows, the trending topics according to information obtained from the internet, which is drawn by the Lingo clustering method based on the platform of Carrot 2 (<http://project.carrot2.org/>). The left-hand figure is based on the first 100 results of a Bing search and shows that “additive manufacturing technology”, “rapid additive manufacturing” and “additive manufacturing processes” are the research hotspots. The right-hand figure is based on the top 100 results of a PubMed search and shows that “tissue engineering”, “resulting implant” and “preparation” are in high usage as keywords relating to 3D printing. The results from this simplistic survey provided a basic understanding for the following research. In this research, scholarly publications were investigated as a more rigorous and reliable representation of the relevant literature as found through the Web of Science.

2.1 Scientometric analysis in CiteSpaceIII

Scientometric is a basic but effective method to detect and identify the emergence and development of a new technology ([Serenko et al., 2010](#)). Although there are an increasing number of science mapping systems and generic tools ([Cobo et al., 2011](#)), few systems are readily accessible and specifically designed to meet the needs for generating a systematic review of a fast-moving and complex field. CiteSpace includes features to facilitate the detection and interpretation of emerging trends and transition patterns for analysts who are not domain experts. It is designed specifically to support the complete analytic process of visualizing and analyzing scientific literature ([Chen, Dubin, et al., 2014b](#)). Therefore, the scientometric software CiteSpace created by Dr. Chen Chaomei ([Chen, 2004](#)) was employed to explore the hotspots and emerging trends on 3D printing in this study.

The intellectual landscape can be depicted by the co-cited references network and co-occurring keywords network ([Chen, Dubin, et al., 2014c](#)). The co-cited references are the ones which are cited at the same time by a later publication. The co-occurring keywords are the ones which occur at the same time in a later publication. The intellectual landscape visualizes the knowledge modules and time sequence of different clusters. It can show the important topics based on the clusters and the emerging trends based on the time sequence. Citation bursts are used to find the hotspots and emerging trends of 3D printing. The start of a burst event is seen through the appearance of a keyword or the surging citations of an article ([Chen, Dubin, et al., 2014a](#); [Chen et al., 2010](#)). The citation burst provides insightful guidance for navigating the development trends of a certain field through the fast-changing landscape of the keywords or references ([Chen, Dubin, & Schultz, 2014](#); [Chen et al., 2006](#)). It also provides evidence that the publication evidently has attracted an extraordinary degree of attention from its scientific community so as to be recognized as a hotspot ([Chen, 2004, 2014](#)). The citation burst can last for a single year or multiple years. A publication with a high number of citations can be considered as a landmark in the knowledge field ([Chen et al., 2010](#)). Since these articles can be highly cited over a long period, they may reflect the “long hotspots” of some domains. To sum up, this work explored the hotspots and trends of 3D printing mainly by identifying intellectual landscapes of clusters, burst references and keywords, and landmark references.

2.2 Data collection

In order to retrieve only high-quality literature on 3D printing, SCI-EXPANDED from Web of Science Core Collection was chosen as the data source. The topic query statement of the Advanced Search was TS= (“3D print*” OR “three dimensional print*” OR “additive

manufacturing”). The function of wildcard * was to capture relevant variations of a word, such as 3D printing and 3D printed. Then, “All document types” was selected as the data type and the language set to “English”. The time span of retrieval was set from 1995 to 2016 (the search date was December 13, 2015). The slice is the time interval of data retrieval such as 1 year, 5 years, etc. In our paper, the years per slice was set to 1. The query generated 3144 original records. In order to improve the quality of analysis, 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 2769 including 2648 research articles and 121 review papers.

3. Hotspots and trends

3.1 The intellectual landscape of clusters as indicators of hotspots and trends

The Top N=50 algorithm was selected to generate the intellectual landscape in CiteSpaceIII. Top N=50 means that the 50 most frequently occurring (for keywords) or cited (for reference) will be selected from per slice. Figure 4 shows the overall bibliographic landscape of a co-cited references network for 3D printing, which contains 845 nodes and 2026 links from 1995 to 2016. The nodes denote co-cited references. The year shown with the top color bar from left to right is from the more distant to the more recent past. Lines that connect nodes are co-citation links, whose different colors show when a connection was made for the first time ([Chen, Dubin, et al., 2014c](#)). TFIDF (term frequency–inverse document frequency), LLR (log-likelihood ratio) and MI (mutual information) are the three different algorithms used to generate cluster labels. In this review, LLR is used as the standard because it usually gives the best result in terms of the actual situation after several runs (need a reference for this).

CiteSpace, v. 4.0.R4 (64-bit)
 2015\12\22\0005\30\0520
 C:\Users\acer\Downloads\4.0.R4.64-bit.public.11.25.2015\4.0.R4.64-bit.public.11.25.2015\3dp\download_core\Core dataset\data
 Timespan: 1995-2016 (Slice Length=1)
 Selection Criteria: Top 50 per slice
 Network: N=845, E=2026 (Density=0.0057)
 Pruning: None
 Modularity Q=0.9079
 Mean Silhouette=0.4838

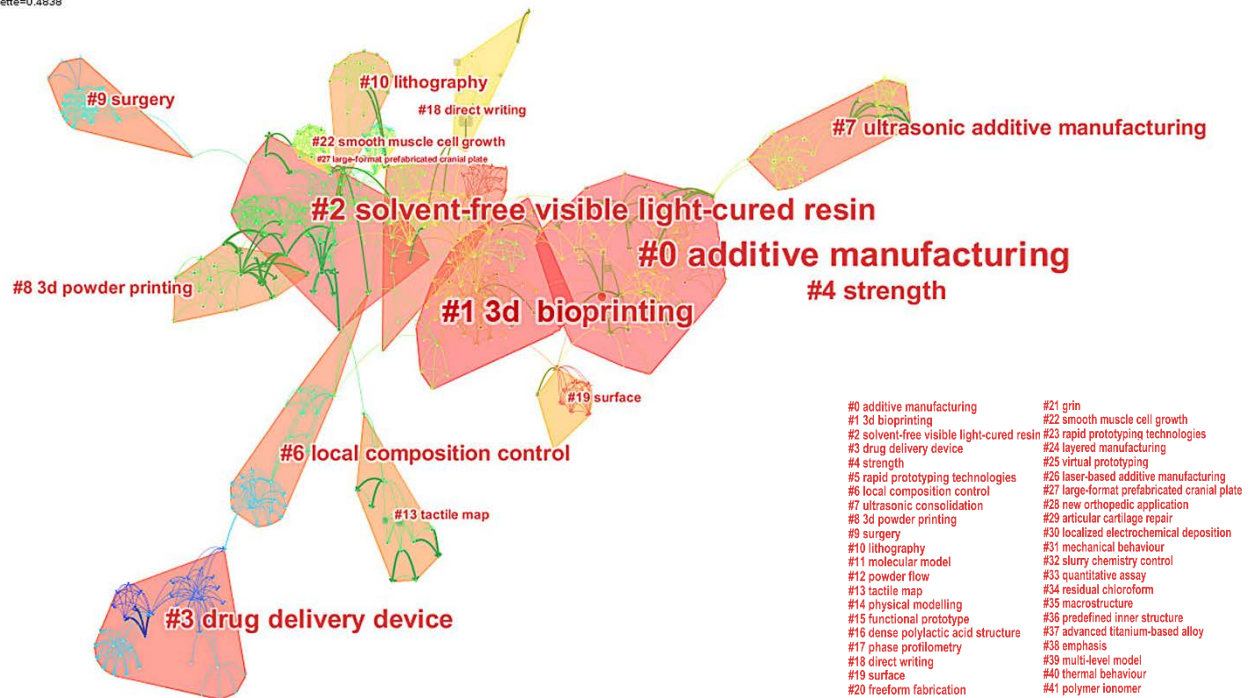


Figure 4 Co-cited references cluster view on 3D printing

The literature co-citation network in Figure 4 contains a total of 39475 documents from 1995 to 2016, and produces 42 clusters. The top 10 of the 42 clusters are shown in Table 1. The size of each cluster represents the number of references, which reflects the intensity of the hotspot. Obviously, “additive manufacturing” is the hottest research topic followed by “3d bioprinting”. The silhouette value ranges from -1 to 1, which reflects the quality of each cluster configuration. The higher the silhouette value, the better the quality of the clustering. The year shows the average publication year of all literature in a cluster. The more recent the date, the more “frontier” is the nature of the clustering, which can embody the emerging trends within the cluster. In Table 1, we can find that “3d bioprinting (2010)”, “additive manufacturing/selective laser (2009)” and “ultrasonic consolidation (2008)”, and “technical parameter (2007)” are the research frontiers for 3D printing.

(1) The hottest cluster “additive manufacturing”

Additive manufacturing is a process of joining materials to make objects from 3D model data, usually layer upon layer ([ASTMInternational, 2012](#)). Based on Table 1, the largest cluster, #0 additive manufacturing, has 68 members, whose average year of publication is 2009. It is not only the largest cluster but also the second most recent, which indicates that additive manufacturing

has been a relatively new term, replacing rapid prototyping and other older terms, and drawn more and more people's attention. In addition, a silhouette value of 0.916 shows that cluster #0 has high quality aggregation. Therefore, the cluster "additive manufacturing" is essential to the literature research.

(2)The emerging research theme "3d bioprinting"

The most recently emerging cluster, #1 3d bioprinting, contains 63 member references. Its average year of publication is 2010. The printing and patterning in three dimensions of all the components that make up a tissue, or to generate structures analogous to tissues, can be termed 3d bioprinting ([Derby, 2012](#)). Nowadays, 3d bioprinting is being applied to regenerative medicine and has made great achievements in the generation and transplantation of several tissues. Multilayered skin, bone, vascular grafts, tracheal splints, heart tissue and cartilaginous structures have already been realized by 3d bioprinting technology ([Murphy and Atala, 2014](#)).

Table 1 Brief summary of top 10 clusters

Cluster	Size	Silhouette	Label			Average year of publication
			TFIDF	LLR	MI	
0	68	0.916	Selective laser	Additive manufacturing	Additive manufacture d metallic part	2009
1	63	0.899	Microfluidic	3d bioprinting	Application area	2010
2	50	0.724	Natural polymer	Solvent-free visible light-cured resin	Mechanical characteristic	2002
3	41	0.973	Solid free-form Fabrication	Drug delivery Device	Slurry chemistry Control	1993
4	41	0.802	Technical parameter	Technical parameter	Bioactive	2007
5	35	1	Rapid prototyping technologies	Rapid prototyping technologies	Rapid prototyping technologies	1995
6	28	0.964	Local composition control	Local composition control	Using rp technology	1997
7	25	0.977	Ultrasonic consolidation	Ultrasonic consolidation	Powder bed	2008
8	21	0.947	3d powder printing	3d powder printing	Bioactive	2005
9	18	0.98	Surgery	Surgery	Surgery	1995

3.2 Landmark references and burst references as indicators of hotspots and trends

Figure 5 shows the landmark references and burst references bibliographic landscape of the

co-cited references network for 3D printing generated by CiteSpaceIII. The different size of “tree rings” node depends on the number of times per year it has been cited. The different colors of “tree rings” are used to match the year shown in the spectrum above the main image. Lines that connect nodes are co-cited links and the different colors of these lines are set to show when a connection was made for the first time. A blue color represents an earlier connection, and an orange color indicates a recent connection. The burst references are marked as red circles and the size of each circle represents the burst strength. In addition, the authors and publication years of burst references are also labeled in black to make them easier to see.

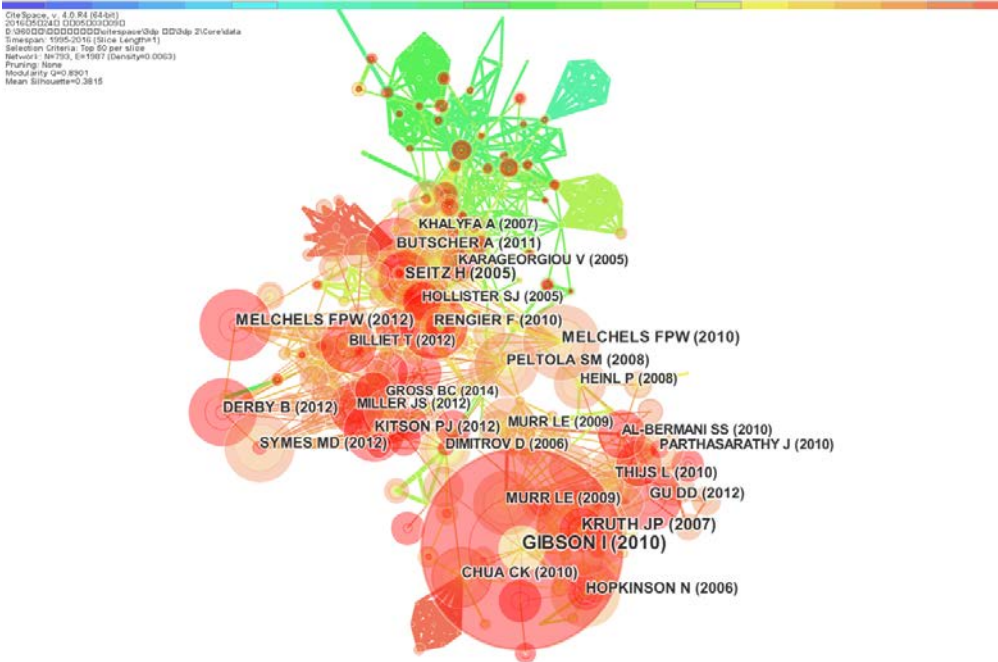


Figure 5 landmark references and burst references bibliographic landscape

3.2.1 Analysis based on landmark references

Table 2 lists the top 10 cited references ranked by citation counts from 1995 to 2016. From the point of view of influence, it is obvious that [Gibson et al. \(2010\)](#), [Kruth et al. \(2007\)](#) and [Melchels et al. \(2010\)](#) are the most important landmark references. In terms of the date aspect of the study, articles 2, 4 and 6 were published from 2005 to 2007, which corresponds to the earlier research hotspots about 3D printing. Articles 1, 3 and 9 were published in 2010, which reflects the hotspots in recent years. Articles 5, 7, 8 and 10 were published in 2012, which indicates the emerging trends. Data analysis shows that 70% of the top 10 cited references were published since 2010, and 72.7% of citation counts in table 2 were also from the articles published since 2010. It is clear that the hotspots of 3D printing have been constantly changing and have also grown quickly since

2010.

From the perspective of research content, the following phenomena can be found.

Landmark references 1, 2, 6 and 10 are all from cluster #0, which reflects the different hotspots coming out of "additive manufacturing". Among of them, the top landmark reference is [Gibson et al. \(2010\)](#), which is a book on "additive manufacturing" published by *Springer*, with a citation count of 141. It has the largest number of citation counts even though it was published in 2010, which indicates the importance of the book in this research field. This book provides a basic overview of the additive manufacturing process, describes the different technologies in detail, and introduces how to apply different technologies in different settings. The second landmark reference with great significance is [Kruth et al. \(2007\)](#) with a citation count of 64. The paper studied which type of "laser-induced consolidation" could be applied to corresponding materials. Landmark reference 6 ([Hopkinson et al., 2006](#)), is another book, entitled "rapid manufacturing: an industrial revolution for the digital age". It covers design potential, customer input and customization, emerging processes, material issues, production economics, management and applications of "rapid prototyping". This book is a groundbreaking text that provides excellent coverage of this fast emerging industry, and it is filled with images depicting the vast array of products being commercially manufactured. Landmark reference 10 ([Gu et al., 2012](#)) studied "laser additive manufacturing" of metallic components, establishing a relationship between material, process, and metallurgical mechanisms for laser based additive manufacturing of metallic components.

Articles 5, 7, 8 and 9 are all from cluster #1, and are the research hotspots coming out of the "3d bioprinting" field. The fifth landmark reference was published in *Progress in Polymer Science* by [Melchels et al. \(2012\)](#) as a review paper. It discusses the rationale for engineering "tissues and organs" by combining computer-aided design with additive manufacturing technologies. Article 7 ([Symes et al., 2012](#)) put forward an attractive but unexplored application using a 3D printer to initiate "chemical reactions" by printing the reagents directly into a 3D reactionware matrix, thus putting reactionware design, construction and operation under digital control. Article 8 was published in *Science* by [Derby \(2012\)](#) and is also a review paper like article 5. It reviews the printing and prototyping of "tissues and scaffolds". Article 8 ([Rengier et al., 2010](#)) points out that 3D rapid prototype models could be produced by special printers based on CT or MRI volumetric "medical images".

Articles 3 and 4 are from cluster #4. They both researched problems on "technical parameters". Article 3 ([Melchels et al., 2010](#)) discussed the characteristic features of the "stereolithography" technique and compared it with other SFF techniques. Article 4 ([Seitz et al., 2005](#)), entitled

“three-dimensional printing of porous ceramic scaffolds for bone tissue engineering” was the earliest published of the top 10 references. It proposed a new process chain for custom-made three-dimensional “porous ceramic scaffolds” for bone replacement.

Table 2 Top 10 cited references ranked by citation counts

Sequence	References	Citation counts	Cluster#
	Gibson I, 2010, ADDITIVE MANUFACTURING		
1	TECHNOLOGIES: RAPID PROTOTYPING TO DIRECT DIGITAL MANUFACTURING, V, P1	141	0
2	Kruth JP, 2007, CIRP ANN-MANUF TECHN, V56, P730	64	0
3	Melchels FPW, 2010, BIOMATERIALS, V31, P6121	54	4
4	Seitz H, 2005, J BIOMED MATER RES B, V74B, P782	50	4
5	Melchels FPW, 2012, PROG POLYM SCI, V37, P1079	50	1
6	Hopkinson N, 2006, RAPID MANUFACTURING: AN INDUSTRIAL REVOLUTION FOR THE DIGITAL AGE, V, P1	49	0
7	Symes MD, 2012, NAT CHEM, V4, P349	49	1
8	Derby B, 2012, SCIENCE, V338, P921	48	1
9	Rengier F, 2010, INT J COMPUT ASS RAD, V5, P335	47	1
10	Gu DD, 2012, INT MATER REV, V57, P133	46	0

3.2.2 Analysis based on burst references

The emerging trends in a research area can be captured by articles receiving a surging frequency of citations ([Kim and Chen, 2015](#)). Those articles cited more frequently than others in a relatively short period of time are called burst references. The burst references with the highest strength values, may be seen as the foci of research in a community, since these articles have attracted the attention of peer scholars. For drawing a more representative conclusion, we will only focus on the literature with the strongest burst in a group of articles bursting at the same time. Table 3 shows the top 10 references with the strongest burst values for particular start years during the period 1995-2016, listed chronologically. Table 3 provides an insight into the changing trends of the hotspots in 3D printing research. The dark green line represents the time after an article is published, and the red line represents the burst duration for the article.

From the Table 3, we see that the paper bursting earliest during 1995-2016 was [Sachs et al.](#)

(1992), published in the *Journal of Manufacturing Science and Engineering*. Its burst started in 1996 and ended in 2000 as the red line shows, reflecting the earliest hotspot for 3D printing research. This article pointed out that “3D printing” is a process for the manufacture of tooling and functional prototype parts directly from computer models, and it may be applied to the production of metal, ceramic, and metal/ceramic composite parts. The paper also discussed how 3D printing works. Table 3 also shows that there was no strong burst literature in the top 10 from 1997 to 1999, which indicates that research on 3D printing was not widely spread over many topics during that time.

Table 3 Top 10 of references with the strongest burst in the same start year

References	Citation Bursts		
	Strength	Begin	End
SACHS E, 1992, J ENG IND-T ASME, V114, P481	7.0833	1996	2000
KATSTRA WE, 2000, J CONTROL RELEASE, V66, P1	6.0046	2000	2008
TABOAS JM, 2003, BIOMATERIALS, V24, P181	6.4494	2005	2011
LEONG KF, 2003, BIOMATERIALS, V24, P2363,	9.6022	2006	2011
YEONG WY, 2004, TRENDS BIOTECHNOL, V22, P643	5.406	2007	2012
SEITZ H, 2005, J BIOMED MATER RES B, V74B, P782	13.7982	2008	2013
HOPKINSON N, 2006, RAPID MANUFACTURING, V, P1	10.0732	2011	2014
SANTOS EC, 2006, INT J MACH TOOL MANU, V46, P1459	8.648	2012	2014
SYMES MD, 2012, NAT CHEM, V4, P349	8.9843	2013	2014

Four years later, [Katstra et al. \(2000\)](#) published a paper entitled “Oral dosage forms fabricated by Three Dimensional Printing™”, which burst quickly in the same year and kept going for nine years until 2008 as shown in Figure 6 and was consequently, the most persistent hotspot. In this paper, 3D printing is considered as a novel technique used in the fabrication of “complex oral dosage delivery pharmaceuticals”. The authors found 3D printing is capable of accurately constructing dosage forms with active content and samples fabricated with this technique are comparable to other standard pharmaceutical products. Five years after that, an article by [Taboas et al. \(2003\)](#) burst from 2005 until 2011. This paper developed several methods for casting locally and globally porous, biomimetic and composite “3D polymer-ceramic scaffolds”. These could provide precise control over scaffold shape, material, porosity and internal pore architecture. The above two papers reflect the following phenomena: first, the medical field began to be a research hotspot for 3D printing in 2000-2011; second, during the period from 2001 to 2004, there was still no strong burst literature in the top 10 strongest burst references, which suggests that 3D printing research had not yet appeared as a comprehensive outbreak at that time.

Since 2005, burst literature has emerged every year in the top 10 strongest burst references except in 2009-2010. The research hotspots for 3D printing continue to increase corresponding to research entering the stage of a comprehensive outbreak. [Leong et al. \(2003\)](#) reviewed the application/potential application of advanced solid freeform fabrication (SFF) techniques in creating “tissue engineering (TE) scaffolds”. The citation burst of this paper lasted for 5 years from 2006 to 2011. [Seitz et al. \(2005\)](#) already appearing in Table 3 as “porous ceramic scaffolds” burst here in 2008, lasting for 5 years as shown in Figure 7 with a high burst strength of 13.7982. Its burst strength is the second strongest, which shows that a large number of scholars were interested in this article. These two articles show that the related research on "scaffolds" has become a hotspot in the field of 3D printing continuously in recent years. [Yeong et al. \(2004\)](#) bursting in 2007 and [Hopkinson et al. \(2006\)](#) bursting in 2011 together make “rapid prototyping” a research hotspot. In 2012, with the emergence of a paper entitled "Rapid manufacturing of metal components by laser forming" by [Santos et al. \(2006\)](#), “laser-forming techniques” that include selective laser sintering, selective laser melting and 3-D laser cladding became the newest hotspot. After that, The article with the strongest citation burst in 2013 was written by [Symes et al.](#)

(2012) on “chemical reactions”. It burst late in 2013 and lasted for only 2 years. It is also one of the top 10 cited references. This fully reflects the importance of this article in the research field of 3D printing. The newest burst reference (Gibson et al., 2010) on “additive manufacturing” needs to be emphasized again as the most important landmark reference in the above, for it has the highest burst strength of 13.9937 even though it was the most recent burst, beginning in 2014. It shows that the research contents of this literature has been highly recognized and valued by academic circles.

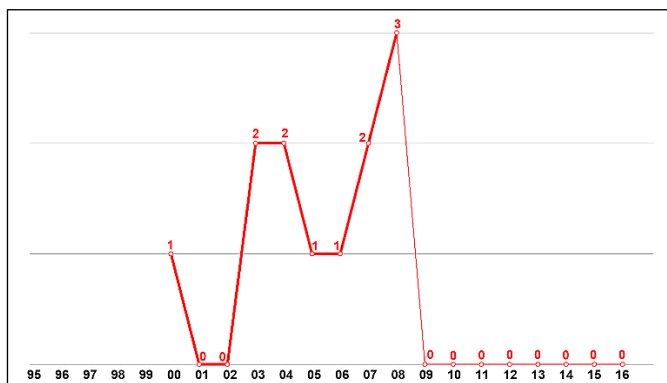


Figure 6 Citation history of Katstra et al. (2000)

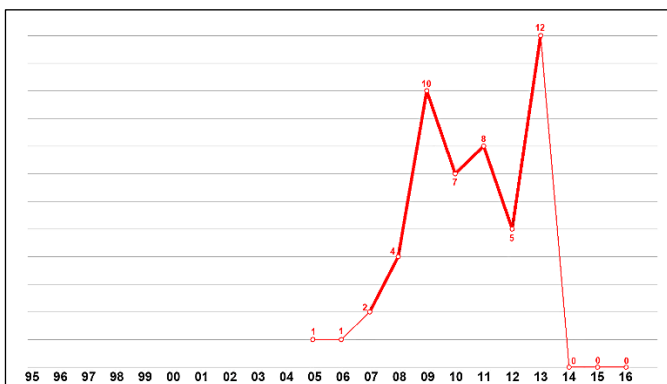


Figure 7 Citation history of Seitz et al. (2005)

3.4 Keywords as indicators of hotspots and trends

Figure 8 shows the knowledge landscape of co-occurring keywords network for 3D printing. The network generated for literature published from 1995 to 2016 contains a total of 537 keywords and 1736 links. The nodes are keywords and the different colors of these “tree rings” are used to match the year shown in the spectrum above the main image. The thickness of “tree rings” represents the number of uses of a co-occurring keyword in a particular year. Lines that connect nodes are called co-occurring links and the different colors of these lines are set to show when a connection was made for the first time. A blue color represents an earlier connection, and an

area of 3D printing research. “Aluminum” and “titanium” can be classified as material category, which shows that the material issues are still an important issue in the industrialization of 3D printing. “Hydroxyapatite scaffold”, “biomedical application” and “stem cell” belongs to medicine category, which proves that the medical industry is the most representative in the application research. Based on the burst duration and burst strength of these keywords, “Solid freeform fabrication” burst earliest in 2003, lasts the longest from 2003 to 2012 and owns the biggest burst value, which illustrates “solid freeform fabrication” technology is an important 3D printing technology, receiving extensive attention. What’s more, “stem cell” burst latest in 2014 and continues so far, which means “stem cell” is a hotspot and emerging trend of 3D printing research.

Table 4 Top 10 keywords with strong bursts in 3D printing research

Keywords	Strength	Begin	End	1995 - 2016
solid freeform fabrication	6.658	2003	2012	
aluminum	5.5632	2006	2011	
hydroxyapatite scaffold	4.0947	2010	2011	
titanium	3.5642	2010	2011	
electron beam melting	4.1248	2010	2012	
selective laser sintering	4.5711	2011	2012	
surface roughness	4.4231	2011	2013	
biomedical application	3.7508	2011	2014	
computer aided design	4.3512	2011	2013	

stem cell 4.2428 2014 2016

4. Conclusion and discussion

4.1 Conclusion and Findings

Hotspots and trends of 3D printing have been identified based on structural and temporal properties derived from the relevant publications from 1995 to 2016 using CiteSpaceIII. In order to summarize clearly the findings of the different indicators from the clusters, burst references, keywords, and landmark references, and to aid analysis, we have drawn a comprehensive map visualizing hotspots and trends of 3D printing as shown in Figure 9.

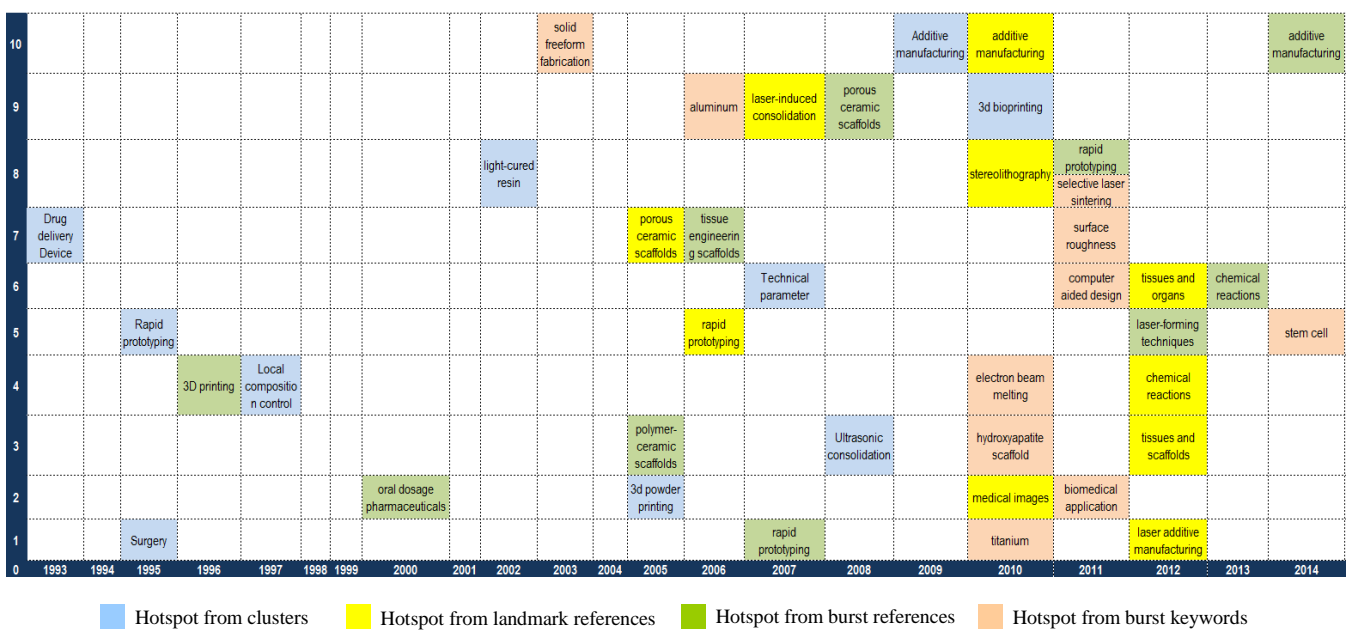


Figure 9 Overall perspective of hotspots and trends of 3D printing

Figure 9 is a summary of the results from clusters, landmark references, burst references and burst keywords. The x-axis represents time (year) and the y-axis represents the relative importance of hotspots, divided into 10 levels. For cluster analysis, hotness level is judged according to the size of clustering; for landmark references, it is judged by citation counts; for burst references and burst keywords, it is decided according to their burst strength. Based on the above, we can draw the following comprehensive conclusions. (1) hotspots appeared first in 1993, and grew rapidly from 2005, and peaked in 2013; (2) without considering those conceptual terminology such as rapid prototyping, 3D printing, additive manufacturing, etc., hotspots are mainly concentrated in the medical field (appearing 11 times including “surgery”, “scaffold”, “drug”,

“stem cell” and so on), the material field (appearing 3 times including “light-cured resin”, “aluminum”, “titanium”), and the technology field (appearing 13 times including “ultrasonic consolidation”, “laser-induced consolidation”, “stereolithography”, “selective laser sintering”, “electron beam melting” and so on); (3) the hotspots in "medical field" appear earliest, and remain extremely active; (4) "3D bioprinting", “titanium”, “stem cell”, "chemical reaction" and so on are the emerging hotspots in recent years. Especially, “stem cell” and "chemical reaction" burst very recently (from 2012), which shows that the chemistry field is becoming the research frontier of 3D printing, and the medical field is still the research forefront of 3D printing.

4.2 Limitations and future outlook

Although the Web of Science Core Collection was chosen as the data source, the authors admit the possibility of missing some important research publications on 3D printing. In addition, we are also aware that relevant records could be missing if the query phrases used for topic searches did not match some records. Also, in order to improve the quality of data, this study selected only articles and books as the research objects, which may also omit some important research results (e.g. PhD theses). Furthermore, “Top 50 per slice” was set as the standard of data extraction in CiteSpaceIII in our research, which will also have had some effect on the analyses. Therefore, the results of the study may not be completely consistent with the actual situation. In a follow-up study, the authors will optimize the related parameters so as to improve the quality of the searches.

The development of 3D printing has shown some new trends in recent years. For example, the cost of 3D printing is rapidly declining, product quality and speed of 3D printing has been able to meet the requirements of more and more customers. Obviously, these new trends are accelerating the industrialization aspect of 3D printing technology. However, the commercial operation of a new technology is often accompanied by complex challenges. As a result, we predict some business operation issues about 3D printing technology, such as business model innovation, brand building, channel management, will be the emerging hotspots in the near future. Also, the development of 3D printing may be also affected by emerging technologies like big data, cloud computing, Internet of Things, artificial intelligence, robotics, virtual reality and so on. Therefore, we believe the fusion of 3D printing and these emerging fields is likely to lead to the birth of new research hotspots.

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