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Research Article

The Conceptual System of Additive Manufacturing via a Quantitative-Qualitative Approach: A Bibliometric Analysis

Felipe Mondragón-Serrano[1,*], América Padilla-Viveros[1], Gerardo Hernández[2], José-Víctor Calderón-Salinas[1,3]

[1]Program on Science, Technology and Society, Centro de Investigación y de Estudios Avanzados-IPN, Unidad Zacatenco, CDMX, MEXICO.
[2]Section Methodology of Science, Centro de Investigación y de Estudios Avanzados-IPN, MEXICO.
[3]Biochemistry Department, Centro de Investigación y de Estudios Avanzados-IPN, MEXICO.

ABSTRACT

Additive Manufacturing (AM) applications have expanded to many areas. Whereas review articles portray the current state of knowledge on AM, scientometric studies identify relevant areas, principal authors, trends, and primary contributing sources from a quantitative perspective. Analysis of the AM still needed to comprise numerous scientific documents and include qualitative criteria. Using a vast number of published documents on AM, we propose a systemized approach to explore AM conceptual subsystems and their historical development. We applied our method to 68,676 records published between 1990 and 2021 in the Web of Science based on revised AM historical terms to prevent including documents unrelated to the subject matter. From a temporal perspective, statistical analysis revealed an explainable change in the AM research trend in 2008. A qualitative study of bibliometric maps obtained with the VOSviewer software led us to determine thirteen conceptual subsystems on AM, whose time development also clarified the history of the whole discipline. These conceptual subsystems distribute in four main publication source clusters, whose leading contributing countries are also reported. Restricting this methodology to specific AM conceptual subsystems or extending it to other knowledge areas is straightforward. Besides, the interactive bibliometric maps, accessible online, enable users to explore the AM conceptual system and find the most cited publications for a better depiction of the current state of knowledge on AM in its different areas.

Keywords: Additive manufacturing, 3D printing, VOSviewer, Scientometrics, Scientific Publications.

Correspondence:
M. Eng. Felipe Mondragón-Serrano
Program on Science, Technology and Society, Centro de Investigación y de Estudios Avanzados-IPN, Unidad Zacatenco, Av. Instituto Politecnico Nacional 2508, San Pedro Zacatenco, 07360 CDMX, MEXICO.
Email: felipe.mondragon@cinvestav.mx
ORCID ID: 0000-0003-4933-6990

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INTRODUCTION

Additive manufacturing (AM) or 3D printing techniques join materials layer upon layer to create objects from a three-dimensional digital model,[1] reducing manufacturing time or cost and producing objects with complex shapes that other methods cannot fabricate.[2]

The varied possibilities brought about by AM have motivated its study from different perspectives: characteristics of the techniques, materials employed, pros and cons of the methods, applications, social impact, and historical and forthcoming development.[3-13]

The vast scientific literature on AM requires scientometric and bibliometric techniques to identify relevant topics in particular areas, principal authors, contributing countries, research concentration areas, and development trends, among other aspects. Studies with these objectives have emphasized AM's main methods, properties, and applications;[14-24] and the impact of AM on the industry, business, environment, and society.[25-34] In addition, overviews on the concentration areas in scientific research, general trends, and their main actors.[35-46]

In its origins, AM developed only prototypes, evolved to manufacturing end-use products, and reached the point where the end consumer is the owner and user of this technology.[4] These changes in AM history have yielded adjustments in the references to its processes and results. Some apparent gaps in the subject's history result from disregarding shifts in concepts and language; different terms might refer to a similar concept, such as "additive manufacturing" or "3D printing," but a term might also refer to other topics, as is the case of "rapid prototyping."

To provide an outlook on the AM scientific literature, to detect its significant changes, to characterize the main concepts involved in it, its primary producers, and the principal publication sources they use, we provide a systemic view of the scientific literature on AM through a quantitative-qualitative approach with a refined, comprehensive list of pertinent historical terms to include as many AM scientific publications as possible and make its timeline

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intelligible. We introduce a technique to diminish the number of false-positive results in the bibliographic query, verifying the terms' accuracy. A neater selection enabled us to unveil a moment of significant change in the research trends within the analyzed period, which extended from the appearance of the first scientific document referring to AM (1990) to December 31st, 2021. VOSviewer, an open-access software for building and visualizing bibliometric maps with a large amount of information,[47] delivers easy-to-interpret maps to analyze the Conceptual System (CS), its development over time, the primary producers of AM research, and how this production distributes in the scientific publication sources.

METHODOLOGY

Bibliographic query

The bibliographic query employed eight historical terms: additive manufacturing, additive fabrication, additive techniques, additive layer manufacturing, layer manufacturing, solid freeform fabrication, freeform fabrication,[1] and 3D printing.

The bibliometric analysis used the VOSviewer software on all documents available in the Web of Science (WoS), a database that allows downloading complete publication records with the cited references in files with no more than 500 publication records and no limit in the number of files. In contrast to WoS, Scopus allows downloading 2,000 complete publication records or 20,000 restricted to citation information alone.

Different writing formats of the eight historical terms appeared in the algorithm for searching in the WoS core collection, including titles, abstracts, keywords, and keywords-plus of all kinds of scientific papers from 1900 to 2021. The initial and the final query strings are shown in Table 1.

The final query string excludes the terms "rapid prototyp*" and "additive* process*" of the initial query string after the statistical refinement.

The wildcard "*" in the WoS refers to the absence or presence of one or more characters; for example, "additive* manufactur*" would allow finding phrases like additive manufacturing, additively manufactured, and additive manufacture. Double quotes force the inclusion of only those documents containing the exact phrase and exclude those where the words appear separately, which may not belong to the studied group. A total of 68,676 publication records resulted in 138 tab-delimited text format files (137 of the files with 500 records and one with 176 records).

Refinement statistical method

The number of terms used in the query is the main factor that increases false positives cases in the results. The accuracy of the query must precede any bibliometric analysis. In our initial query, our search included the terms "rapid prototyp*" and "additive* process*" and yielded 80,999 publication records as shown in Table 1. We randomly sampled 162 tab-delimited text format files from this set (one record for each 500-block) and reviewed the samples' titles and abstracts to determine whether the subject matter belonged to AM. Thirteen (8.02%) of the 162 records turned out to be false positives related to the terms "rapid prototyp*" and "additive* process*"; ditching these terms improved the accuracy of the work.

The sampling process referred to above for the 138 files sampled from 68,676 publication records yielded only two false positives (1.44%). Estimating possible false positives in the whole population used a Montecarlo-like method (SupplementalFile1). Given the proportion w of wrongly placed documents, we randomly distributed them among the 68,676 items. Then we sampled the set, taking one item in each 500-block, and counted the number of wrong items caught by the sample. One thousand such samples for each of one hundred different random locations of $w \times 68{,}676$ items enabled us to compute the probability of finding at most two wrong items. Our result is compatible with values of $w < 0.048$ for an excluding alpha of 0.05. That means that if the entire set of documents has 4.8% or more wrong items, the probability of finding at most two wrong items with our sampling method would be less than 0.05. Data exploration, statistical tests, and simulations used R statistical language.[48] The implemented refinement statistical method is described in Figure 1.

Table 1: Query strings used on the WoS.

Description	Query string	Number of results
Initial query string	TS = ("3d print*" or "3-d print*" or "3-dimensional* print*" or "additive* fabricat*" or "additive* layer* manufactur*" or "additive* manufactur*" or "additive technique*" or "freeform* fabricat*" or "layer* manufactur*" or "solid freeform* fabricat*" or "solid freeform* manufactur*" or "three-dimensional* print*" or "three-d print*" or "rapid prototyp*" and "additive* process*").	80,999
Final query string	TS = ("3d print*" or "3-d print*" or "3-dimensional* print*" or "additive* fabricat*" or "additive* layer* manufactur*" or "additive* manufactur*" or "additive technique*" or "freeform* fabricat*" or "layer* manufactur*" or "solid freeform* fabricat*" or "solid freeform* manufactur*" or "three-dimensional* print*" or "three-d print*").	68,676

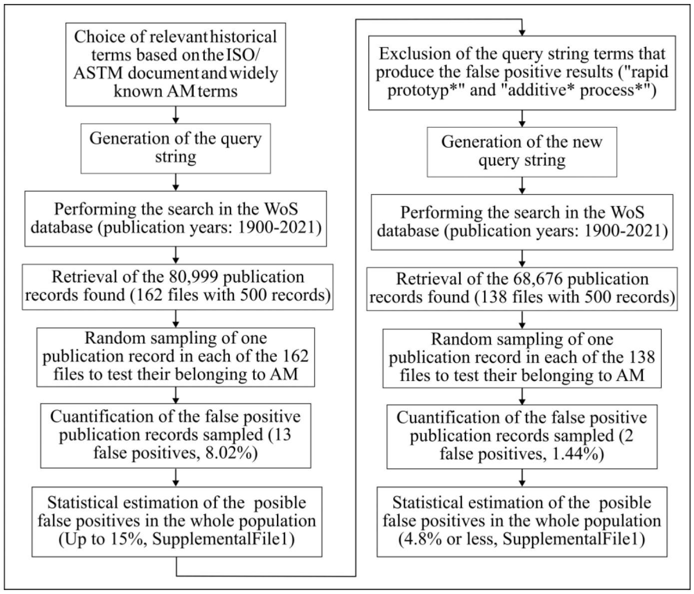

Figure 1: Refinement statistical method.

RESULTS AND DISCUSSION

The disruptive change in AM scientific publications' trend

The first document found by our query string in the WoS was published in 1957 and included in its title the words "a 3-dimensional printed back panel," but clearly, it was not about AM. We found the first document corresponding to AM published in 1990, entitled "Innovations in 3-D printing," part of the national computer graphics association conference held in Anaheim, California. The temporal course of the number of publications from that document to December 31st, 2021, is shown in Figure 2.

In 1990 only five publications referred to AM, and in 2010 there were as many as 296; in this period, publications on the subject followed a monotonous trend. However, that trend changed drastically since then: in the last eleven years, 96.98% of the total scientific publications on AM were published, with 87.95% in the last six years (21.72% of the total papers were published in 2021 alone, 14,918). Figure 2 suggests a trend change in the number of AM publications.

We split the period in Figure 2 into two, taking 2003 as the separation point, which resulted in the first period from 1990 to 2003 and a second from 2004 to 2021; we then compared the slope (exponentially fitted) of the two periods. Similarly, we tested the splitting year from 2004 to 2013, for the pairs of periods obtained (SupplementalFile2). The splitting given in 2008 yielded the most significant statistical difference (t= 5.658), displayed in Figure 3.

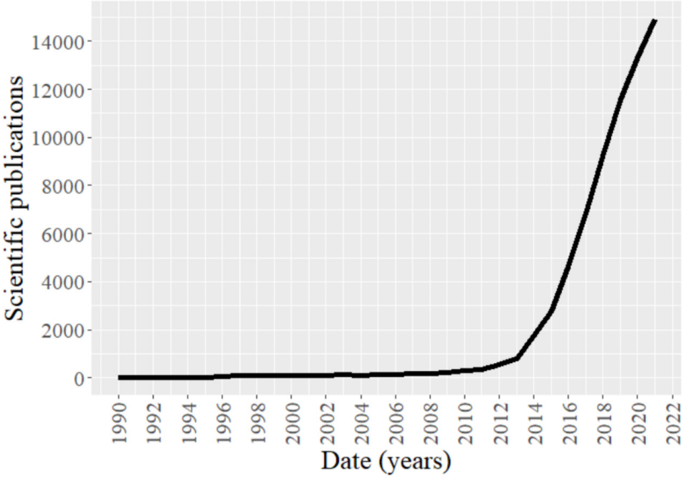

Figure 2: Number of AM scientific publications per year. Elaborated with RStudio.

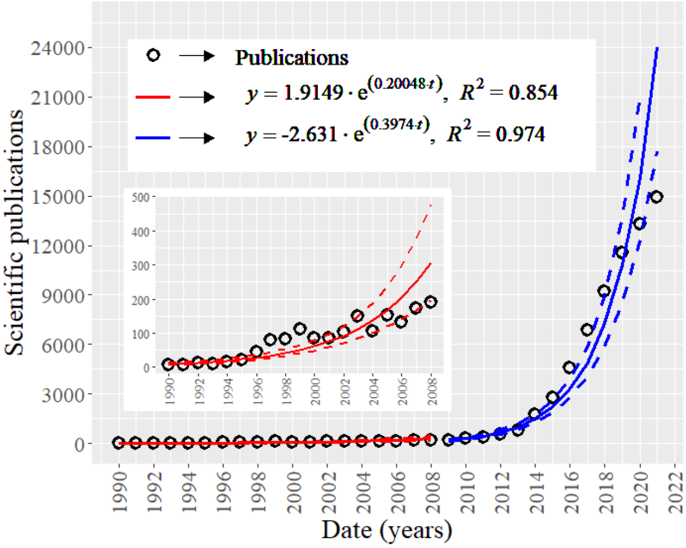

Figure 3: Number of AM scientific publications per year and statistical models. Scientific publications 1990-2021 (open circles), statistical models adjusted to the number of publications, 1990 to 2008 (red line) and 2009 to 2021 (blue line). The graph shows the 95% confidence intervals for each of the models (dashed lines). Elaborated with RStudio.

In Figure 3, the most noticeable differences between the actual values of scientific publications and the ones predicted by the blue statistical model are in 2020 and 2021. The trend of the actual number of publications in the field might indicate an inner decline in publications or could reflect the COVID-19 pandemic's impact on publishing activity. In either case, the blue exponential model of the second period lacks precision in the 2020 and 2021 values, which could influence the trend change estimation. Therefore, we repeated the process explained in the last paragraph cutting off the last one and last two years of the splitting second periods (2021, and 2020-2021) to use a better fit of the blue exponential models for publications' values. The splitting in 2008 kept yielding the most significant statistical differences in both cases, with respective values of t=5.810 and t=5.688. Therefore, 2008 was a year when a significant change occurred in the trend of scientific publications on AM. This change in the trend was possibly driven by the emergence of open-source AM[49-52] and the expiration of several patents on AM between 2006 and 2010,[53-57] which in turn triggered the emergence of new companies manufacturing low-cost 3D printers for personal and office use.[6,58]

The AM CS

We made several bibliometric maps using VOSviewer and the 68,676 publication records to define the AM CS. We identified the most relevant scientific papers and established AM's conceptual subsystems (CSSs, CSS for the singular form).

It was impossible to produce a bibliometric map based on document citations, with zero citations and the highest number of links as limits, including all 68,676 publications. Despite using a mid-range computer (with 16 GB RAM, a 4.1 GHz quad-core processor, and a solid-state drive) and increasing the memory available to VOSviewer following the manual,[59] the software crashed.

Taking the most cited documents as an inclusion criterion, we kept reducing the number of publications to obtain a map that allowed us a smooth interaction with it. Within the range of 15,000 to 35,000 documents, the VOSviewer software structured the clusters of documents similarly and steadily; some clusters disappeared, however, if the number of records was below 15,000. Hence, we chose 15,000 documents with the highest amount of links as a limit, allowing us to establish a comprehensive definition of the AM CS without affecting the maneuverability of the map in its online version. The closeness between map items is directly proportional to their similarities; similar items share a color.[60] By qualitatively reviewing a sufficient number of the most cited documents in each of the seventeen clusters, we designated thirteen CSSs, as shown in Figure 4.

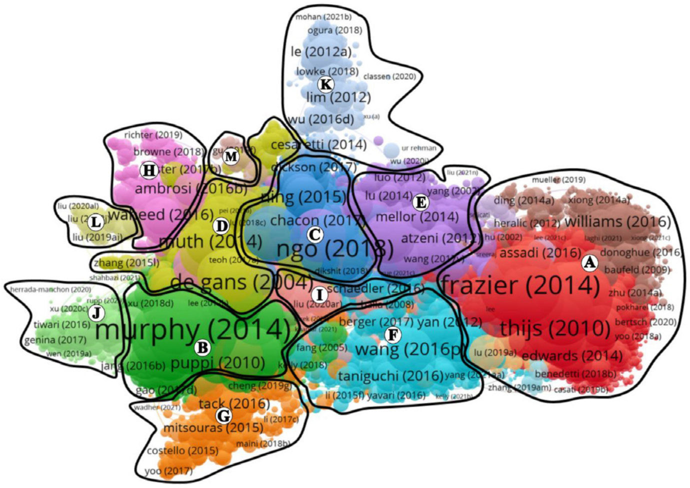

Figure 4: Bibliometric map produced by VOSviewer displaying the thirteen AM CSSs. This bibliometric map is based on document citations (15,000 items). The items show the first author's last name and the document's publication year. The size of the items and text labels is proportional to the number of citations the documents have received. The links represent citations between documents. The letters inside the white circles ("A" to "M") represent the CSSs with the following names: A. *Metals*. B. *Tissue engineering and artificial organs*. C. *Polymers*. D. *Composite, active, and functional materials*. E. *Technology management, optimization, and social implications*. F. *Scaffolds*. G. *Medical models*. H. *Biotechnology and chemistry*. I. *Ceramics*. J. *Pharmaceuticals*. K. *Construction industry*. L. *Food*. M. *Emissions*. Refer to the SupplementalFile3 for more detailed information on these CSSs. For an interactive version of this VOSviewer map use the link: https://app.vosviewer.com/?json=https://drive.google.com/uc?id=1EY0r7Th50DEg-EeCEtkh8Y_YSzBO592N.

Related CSSs are situated closer together in Figure 4. For example, *Metals* (A) is related to *Scaffolds* (F), metallic-made materials intended as prostheses. *Tissue engineering and artificial organs* (B) is closely related to *Composite, active, and functional materials* (D), *Medical models* (G) and *Pharmaceuticals* (J), as well as developing scaffolds with biomaterials (F). The CSS *Technology management, optimization, and social implications* (E) covers a variety of subjects that involve different techniques, accounting for its location among *Metals* (A), *Polymers* (C), *Ceramics* (I), and *Construction industry* (K). Knowing the distribution of the CSSs in Figure 4 and using the VOSviewer density visualization option in this Figure 4, we could identify the location of the most cited documents among the CSSs, as shown in Figure 5.

According to Figure 5, the CSSs with the most cited documents in AM are *Metals* (A)> *Tissue engineering and artificial organs* (B)> *Composite, active, and functional materials* (D)> *Polymers* (C)> *Technology management, optimization, and social implications* (E). The prominent place of *Metals* could be accounted for by the mechanical properties of the parts created through this technique, the end-use nature of these products, and the potential to significantly impact industrial production models.[6] The highly-cited documents in CSSs C and E might be the review articles covering AM techniques, their characterization, and their social implications. CSSs D and B are primarily related to developing new materials and the healthcare sector; the prompt

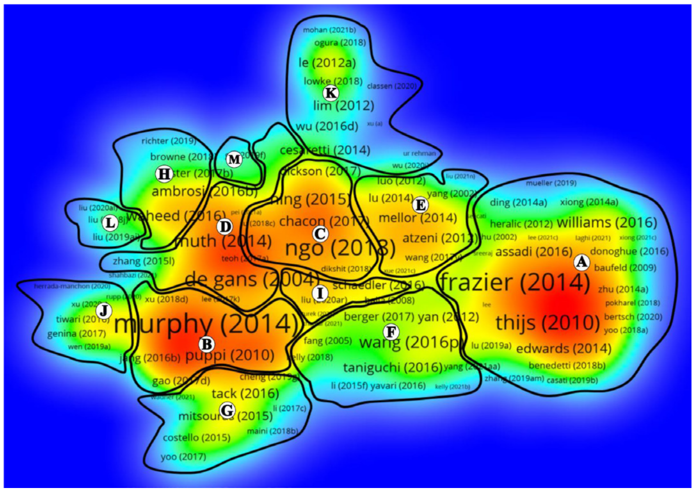

Figure 5: Bibliometric map produced by VOSviewer displaying the thirteen AM CSSs (density visualization). Greater number of highly cited documents (red), lower number of highly cited documents (blue). Modified from VOSviewer.

demand for new materials and treatments could explain many citations. The complete information on the thirteen CSSs appears in Table 2.

The *Metals* CSS contains the most items and citations, 4,416 and 195,788, respectively, though its average of 44 citations per document is below the average of other CSSs. Accordingly, the most salient CSSs within AM are as follows: *Tissue engineering and artificial organs* (68 citations per document), *Composite, active, and functional materials* (56), *Technology management, optimization, and social implications* (45), *Scaffolds* (45), *Metals* (44) and *Biotechnology and chemistry* (42).

To understand the temporal development of the AM CS, we filtered by year and by CSS the 15,000 most cited scientific publications in Figure 4, from 1990 to 2021; the evolution over time of the most cited scientific publications of AM within each of the thirteen CSSs appears in Figure 6.

In 2005, there were documents associated with 10 CSSs, and by 2007, documents associated with 12 CSSs. Between 2014 and 2021, the thirteen CSSs account for 85 to 99% of the total scientific publications (Figure 6).

The first scientific publications associated with *Ceramics*, *Technology management, optimization, and social implications*, *Metals*, and *Polymers*; this is consistent with the materials involved in AM and the optimization of its techniques. The historical development of these CSSs has been different. *Metals* accounted for the highest publication rate, citations, and documents (971) by 2021 (Table 2). The remarkable predominance in its number of publications started in 2016 and continues until 2021, possibly due to its products' mechanical resistance and industrial applications.[6,9,12] *Polymers* has 40.45% of *Metals*' estimated annual publication rate (384 documents in 2021), probably because polymers are usually less resistant than metals. However, their mechanical properties continue to be optimized,[9] and the low cost of materials and open-source resources make the Fused Filament

Table 2: Information on the thirteen CSSs. The information in this table resulted after refining the data from the VOSviewer. "map" file that generates Figure 4. Average citations are obtained by dividing the number of citations by the number of items in each of the CSSs. The annual publication rate is the slope of a linear model estimated with the number of scientific publications from 2014 to 2021 for each of the CSSs since more than 85% of the publications in each case appeared in these eight years.

Letter in Figure 4	Main cluster color	Name	VOSviewer clusters	Percentage with respect to the 15,000 items	Number of citations	Number of items	Average citations	Annual publication rate
A	🟥	*Metals*	1, 8, 14, 15, 16	29.4	195,788	4,416	44	131
B	🟩	*Tissue engineering and artificial organs*	2	12.2	124,591	1,834	68	30
C	🟦	*Polymers*	3	10.6	62,778	1,593	39	53
D	🟨	*Composite, active, and functional materials*	4	10.4	87,780	1,562	56	39
E	🟪	*Technology management, optimization, and social implications*	5	7.3	49,500	1,103	45	14
F	🟦	*Scaffolds*	6	6.8	46,089	1,022	45	27
G	🟧	*Medical models*	7	6.7	35,211	1,007	35	12
H	🟪	*Biotechnology and chemistry*	9	4.6	29,392	696	42	11
I	🟥	*Ceramics*	10	4.1	23,101	608	38	15
J	🟩	*Pharmaceuticals*	11	3.5	20,775	519	40	20
K	🟦	*Construction industry*	12	2.6	15,695	386	41	16
L	🟨	*Food*	13	1.2	6,439	184	35	8
M	🟫	*Emissions*	17	0.5	2,157	70	31	2

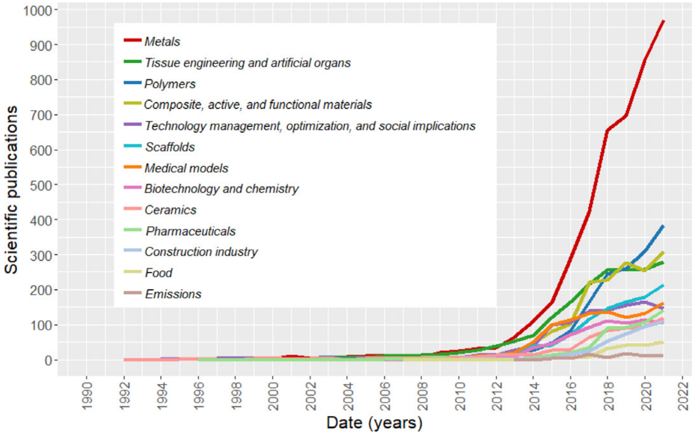

Figure 6: Number of AM scientific publications per year in each of the thirteen CSSs. The information on this figure is based on the 15,000 items shown in Figure 4. The lines colors correspond to the main cluster colors in Figure 4. Elaborated with RStudio.

Fabrication (FFF) technique increasingly accessible, broadening polymers' applications. The publication rate of *Ceramics* is 11.45% (117 documents), compared to *Metals;* this may be because these products are less ductile and dense than metals, and the limited variety of materials.[9]

The optimization of techniques, processes and products, and the interest in the social implications of AM are mixed in *Technology management, optimization, and social implications* (with 146 documents). This CSS originated early on and has a meager publication rate (14). In recent years, it has entered a plateau, which may be due to the fact that, in the current state, it is not possible to deepen its development and that the foundations of its implications have been established.

In 1997 the first article associated with *Composite, active, and functional materials* was published. This CSS was crucial to creating products made up of layers of different materials; its publication rate is 39 (310 documents), and its applications include: sensors, actuators, robots, batteries, electronic circuits, and 4D printed products. This CSS possibly gave rise to *Tissue engineering and artificial organs* from hydrogels and thermo- and photosensitive polymers, and later to *Pharmaceuticals* and *Medical models* CSSs, by adding bioactive substances or generating functional anatomical models.

Scaffolds started to have associated documents in 2005 and has a publication rate of 27, very similar to *Tissue engineering and artificial organs* (214 documents). The latter allowed the development of the *Scaffolds* CSS, which is more specialized and is currently necessary for generating tissues.

Pharmaceuticals, *Medical models* and *Biotechnology and chemistry* CSSs, with publication rates of 20, 12, and 11, respectively, increased their publication rate in 2014, probably impacted by the implementation of desktop and low-cost 3D printers; their current low publication rates possibly reflect reaching a top application level that demands technological development and accessibility.

The most recently formed CSSs are *Construction industry*, *Food*, and *Emissions.* They have low publication rates (16, 8 and 2, respectively; and only 108, 51 and 14 documents). These three CSSs increased the number of publications in 2015. Note that there is no significant trend change in the Emissions CSS after 2017, perhaps for the limited amount of techniques and materials that can be emission evaluated.

Using VOSviewer we also produced the bibliometric map based on text data to identify the most frequently used terms in the CSSs of the AM scientific literature (Figure 7). The parameters for the map were the binary count method, including only the title and abstract of the 68,676 publication records and excluding copyright statements and structured abstract labels, setting a minimum of 500 occurrences per term and showing only the first 307 terms (60% of the most relevant, according to the algorithm described by van Eck and Waltman).[61] We analyzed the terms and used a "thesaurus file" (Supplemental File4) to omit the recurrent ones (additive manufacturing process, layered manufacturing, additively, 3d printer, and others) and refine the synonyms.

The terms of the bibliometric map of Figure 7 refer mainly to the CSSs *Metals* (green cluster); *Scaffolds* and *Tissue engineering and artificial organs* (blue cluster); *Medical models* (red cluster); and *Composite, active, and functional materials* together with *Polymers* (red and yellow clusters). The terms "electron beam," "slm" (selective laser melting), and "fdm" (fused deposition modeling) trademarked by Stratasys Inc. refer to different AM techniques. The FDM technique, also known as FFF, has played a crucial role

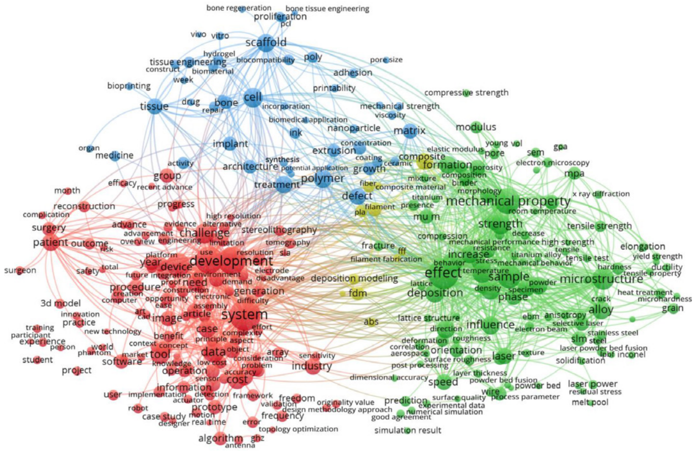

Figure 7: Bibliometric map of the 307 AM terms that VOSviewer designated as the most relevant. The size of the items and text labels is proportional to the number of term occurrences. The distance between terms indicates their relatedness; the smaller the distance, the strongest the terms are related. The link thickness is proportional to the number of times the terms occur together. Modified from VOSviewer. For an interactive version of this bibliometric map, use the following link: https://app.vosviewer.com/?json=https://drive.google.com/uc?id=1m_PWqzJtZf3cS5k_cij-tWWrjfdM-Jm1.

in the scientific development of AM for various reasons, and its patent expired around the trend switch. The terms "fdm" and "fff" in the yellow cluster are close to the map center, which reveals their strong relationships with the other terms; it was the most used technique in the open-source projects cited in the trend change analysis in Figure 3, and it is the principal technique used in the *Polymers* CSS.

Figure 8 shows the 50 most cited publication sources distributed in the CSSs, based on the 68,676 publication records and using the VOSviewer default settings.

The publication sources with more AM publications are "Additive Manufacturing" with 1,894 documents; "Materials" with 1,254 documents; "International Journal of Advanced Manufacturing Technology" with 1,035 documents; "Rapid Prototyping Journal" with 1,008 documents; and "Materials and Design" with 874 documents (Figure 8). These five publication sources are also in the top ten with the highest total citations, corresponding to the first, tenth, fifth, fourth, and second places. Table 3 shows the 50 publication sources and their respective citation information.

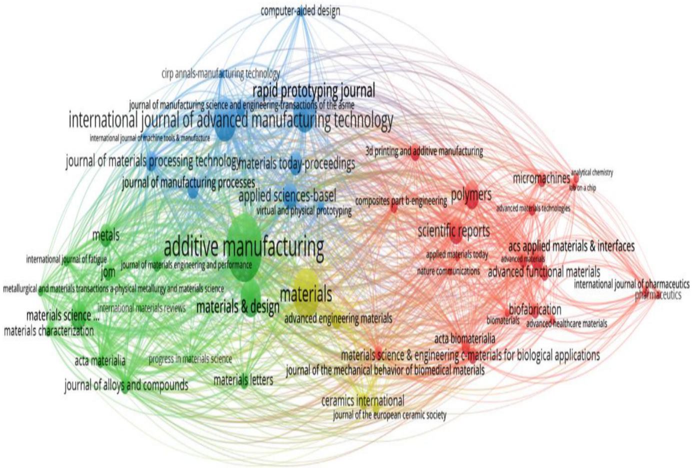

Figure 8: Bibliometric map of the 50 publication sources with the highest AM citation amount. Item and text label sizes are proportional to the number of documents published in each source. The link thickness is proportional to the number of citations between sources. Modified from VOSviewer. For an interactive version of this bibliometric map, use the following link: https://app.vosviewer.com/?json=https://drive.google.com/uc?id=1F3sAVPyu1a1KyNix8KhffGXN9y-VSzZA.

Table 3: Citation information on the 50 publication sources with the highest citation amount. Average citations are obtained by dividing the number of citations by the number of documents in each of the publication sources.

Cluster color in Figure 8	Name of the publication source	Number of documents	Number of citations	Average citations
🟩	Additive manufacturing	1894	38087	20
🟨	Materials	1254	14207	11
🟦	International journal of advanced manufacturing technology	1035	19201	19
🟦	Rapid prototyping journal	1008	20079	20
🟩	Materials and design	874	33548	38
🟩	Materials science and engineering a-structural materials properties microstructure and processing	611	18375	30
🟥	Polymers	556	4470	8
🟥	Scientific reports	521	13374	26
🟦	Applied sciences-basel	518	2769	5
🟥	Acs applied materials and interfaces	488	12498	26
🟦	Materials today-proceedings	448	1963	4
🟩	Metals	418	2903	7
🟦	Journal of manufacturing processes	383	4571	12
🟦	Journal of materials processing technology	348	16354	47
🟥	3d printing and additive manufacturing	313	3287	11
🟩	Journal of materials engineering and performance	310	4685	15
🟨	Advanced engineering materials	302	4974	16

continued...

Table 3: Cont'd.

Cluster color in Figure 8	Name of the publication source	Number of documents	Number of citations	Average citations
🟦	Journal of manufacturing science and engineering-transactions of the asme	300	7061	24
🟩	Materials letters	282	4287	15
🟩	Jom	280	5197	19
🟥	Materials science and engineering c-materials for biological applications	268	7756	29
🟩	Journal of alloys and compounds	268	7628	28
🟨	Ceramics international	267	4265	16
🟥	Advanced functional materials	257	9415	37
🟥	Biofabrication	254	11748	46
🟥	Micromachines	242	2221	9
🟥	Acta biomaterialia	239	13833	58
🟥	Advanced materials	235	24832	106
🟥	Journal of the mechanical behavior of biomedical materials	227	5772	25
🟥	Composites part b-engineering	225	9408	42
🟥	Advanced materials technologies	207	3079	15
🟩	Acta materialia	202	17310	86
🟥	International journal of pharmaceutics	194	7610	39
🟨	Journal of the european ceramic society	179	4103	23
🟦	Virtual and physical prototyping	174	4109	24
🟩	International journal of fatigue	164	5211	32
🟩	Materials characterization	156	4053	26
🟩	Metallurgical and materials transactions a-physical metallurgy and materials science	150	4272	28
🟥	Advanced healthcare materials	145	4378	30
🟥	Analytical chemistry	136	5254	39
🟦	Computer-aided design	132	5639	43
🟥	Biomaterials	128	16127	126
🟥	Lab on a chip	128	6147	48
🟥	Nature communications	127	7853	62
🟥	Pharmaceutics	122	1500	12
🟥	Applied materials today	112	2409	22
🟦	Cirp annals-manufacturing technology	111	4982	45
🟦	International journal of machine tools and manufacture	53	4732	89
🟩	Progress in materials science	23	4575	199
🟩	International materials reviews	18	3272	182

Even though “Additive Manufacturing” is the publication source with the highest amount of documents and total citations, it has only an average of 20 citations per document. Other sources excel in the average citations per document: “Progress in Materials Science” (199), “International Materials Reviews” (182), “Biomaterials” (126), and “Advanced Materials” (106). The high average citations received in “Progress in Materials Science” and “International Materials Reviews” is expected, for they focus on publishing review articles. On the other hand, the average citations in “Biomaterials” and “Advanced Materials” is striking, which reinforces the importance of the CSSs *Tissue engineering and artificial organs* and *Composite, active, and functional materials*.

Despite the heterogeneity in the publication sources, it is possible to know which CSS they are part of by looking at their titles and scopes. For example, different publication sources focused on the healthcare sector in the red cluster (CSSs B, D, F, G, H, and J), the AM with metals in the green cluster (CSS A), rapid prototyping in the blue cluster (CSSs C and D), and ceramic materials in the yellow one (CSS I). Notice that there are publication sources in the different clusters of Figure 8 that belong to more than one CSS because they publish in a variety of different AM applications, as in the case of the journals “Additive Manufacturing” and “Rapid Prototyping Journal.”

To identify the countries that contribute the most to the CS, we created the bibliometric map in Figure 9, which displays the distribution of the countries with the highest number of citations in the AM scientific documents by selecting the first 50 countries with a minimum of five documents and using the VOSviewer default settings.

The United States of America, China, Germany, and England have the highest production and citations in AM scientific documents. They produced 19,561; 12,538; 5,435; and 4,741 documents, respectively (Figure 9). These four countries host the links with the highest reciprocal citations in their scientific literature. The United States of America leads a cluster of twenty-four countries that host the most extensive number of scientific documents (red). With only five countries, an Asian-Oceanic cluster led by China has the second-largest number of scientific documents (yellow), followed by a cluster of eight countries led by Germany (green). The rest of the AM scientific documents distributes in blue>turquoise>orange>and purple clusters, headed by France, Japan, Canada, and Scotland. The European continent contributes the most to AM scientific publications. Among the 50 countries with the highest citations in AM scientific documents, twenty-seven belong to Europe, fourteen to Asia, five to America, two to Africa, and two to Oceania. The complete information on the 50 top-producing countries in the AM CS is in Table 4.

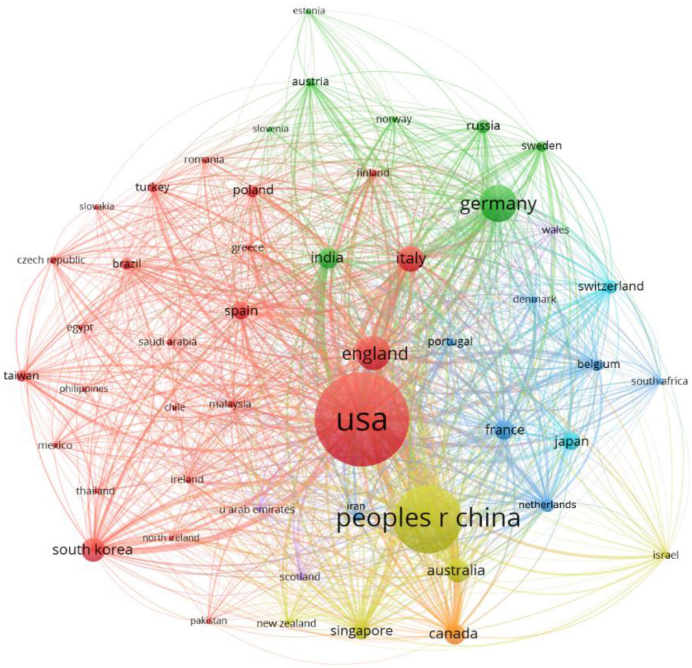

Figure 9: Bibliometric map of the 50 countries with the highest number of citations in AM scientific documents. The size of the items and labels is proportional to the number of documents published in each country. Link thickness is proportional to the number of citations between countries. Elaborated with VOSviewer. For an interactive version of this bibliometric map, use the following link: https://app.vosviewer.com/?json=https://drive.google.com/uc?id=1Y7V2_hWmcuSjdhm-ZZ49CLwfPKXy52qk.

The countries’ impact of publications does not necessarily correspond to the average number of citations: a Belgium and the United States of America comparison shows Belgium with a 12-point lead over the 20 average citations per document of the United States. Nevertheless, the latter has 21 times the number of scientific documents and 13 times the total number of citations than Belgium. Note that the VOSviewer software considers the co-authorships of a document as one document for each of the authors’ countries, which may distort the observation.

The United States of America produces most of the scientific documents on AM, and this country granted the first patents referring to AM techniques.[7] The United States of America, China, Germany, and England are among the top six countries applying for patents on AM,[62] consistent with their significant published contribution. Since a wide range of areas of high scientific interest that produce new technological advances use AM (for that, AM is named the “new industrial revolution”),[4] these leading countries integrate AM as part of their technological innovation plan.

Using the most general terms to refer to AM, we intended to avoid a bias towards its different areas. However, we cannot rule out a bias caused by using the WoS database instead of Scopus, which contains more scientific documents. The methodology implemented in this work reduced the inclusion of documents unrelated to the subject matter; however, we still need to provide a method to control the exclusion of relevant publications in the

Table 4: **Citation information on the 50 countries with the highest citation amount. Average citations are obtained by dividing the number of citations by the number of documents in each of the countries.**

Cluster color in Figure 9	Continent to which the country belongs	Name of the Country	Number of documents	Number of citations	Average citations
🟥	American	Usa	19561	383954	20
🟨	Asian	Peoples r china	12538	177655	14
🟩	European	Germany	5435	91561	17
🟥	European	England	4741	99420	21
🟥	European	Italy	3268	48817	15
🟥	Asian	South korea	2884	37545	13
🟨	Oceanic	Australia	2668	58484	22
🟩	Asian	India	2432	25431	10
🟧	American	Canada	2370	33502	14
🟦	European	France	2277	33672	15
🟥	European	Spain	1945	22509	12
🟦	Asian	Japan	1852	19683	11
🟨	Asian	Singapore	1780	44694	25
🟦	European	Netherlands	1372	34845	25
🟩	European	Russia	1357	8327	6
🟦	European	Switzerland	1300	27359	21
🟥	European	Poland	1135	11736	10
🟥	American	Brazil	1063	10010	9
🟥	Asian	Taiwan	1029	9986	10
🟩	European	Sweden	917	14138	15
🟦	European	Belgium	896	28456	32
🟥	European	Turkey	799	7163	9
🟦	European	Portugal	729	9828	13
🟩	European	Austria	703	11049	16
🟦	Asian	Iran	641	8803	14
🟥	European	Czech republic	600	4402	7
🟥	European	Finland	579	9623	17
🟥	Asian	Malaysia	573	5082	9
🟥	European	Romania	514	2854	6
🟪	European	Scotland	507	7798	15
🟥	Asian	Saudi arabia	493	5893	12
🟥	European	Ireland	472	8419	18
🟨	Asian	Israel	448	8199	18
🟦	African	South africa	444	4689	11

continued...

Table 4: Cont'd.

Cluster color in Figure 9	Continent to which the country belongs	Name of the Country	Number of documents	Number of citations	Average citations
🟦	European	Denmark	426	7707	18
🟨	Oceanic	New zealand	382	5976	16
🟩	European	Norway	374	4950	13
🟥	European	Greece	371	5107	14
🟥	American	Mexico	363	2623	7
🟥	Asian	Thailand	300	1849	6
🟪	European	Wales	259	4390	17
🟥	African	Egypt	258	3356	13
🟪	Asian	U arab emirates	247	3529	14
🟥	European	Slovakia	196	1070	5
🟥	Asian	Pakistan	165	1620	10
🟩	European	Slovenia	160	1385	9
🟥	American	Chile	142	1658	12
🟥	European	North ireland	140	1816	13
🟩	European	Estonia	100	936	9
🟥	Asian	Philippines	64	1424	22

research area when removing terms in the query string. Besides, implementing our method in other research areas could become challenging should those areas have a small number of terms to refer to or only a few publication records.

CONCLUSION

Since AM has shared technical terms with other disciplines, these terms lead to false positives in a bibliographic query; adjusting terms let us minimize the estimated error. A more reliable document selection enabled us to find, around 2008, a significant trend shift in the scientific publications about AM. This year coincides with the emergence of several open-source projects, the expiration of some patents concerning AM techniques, and the appearance of companies manufacturing low-cost 3D printers.

Through a systemic approach to the scientific literature on AM, we could identify thirteen AM CSSs and their development over time: *Metals*; *Tissue engineering and artificial organs*; *Polymers*; *Composite, active, and functional materials*; *Technology management, optimization, and social implications*; *Scaffolds*; *Medical models*; *Biotechnology and chemistry*; *Ceramics*; *Pharmaceuticals*; *Construction industry*; *Food*; and *Emissions*.

The AM CS began by addressing the primary materials used in its different techniques, optimizing its techniques, processes, and products, and studying their social implications. Later, the AM CS turned to create products made up of layers of different materials, four-dimensional products, and products related to the healthcare sector; more recently, the AM CS has focused on the emissions originated during the AM processes and the development of the food and construction sectors.

The CSSs are the subject of four publication source clusters, mainly focused on the healthcare sector, rapid prototyping, and AM of metals and ceramic materials. The leading countries contributing to them are the United States of America>China>Germany> and England; we also found some groups of countries that highly contribute to the scientific literature on AM.

Verifying the accuracy of the query, as in the method used in this work, could provide a baseline for future AM research. Since all the procedures and tools used in this work are open access, this methodology easily transfers to scrutinize specific AM CSSs or other knowledge areas. While the details are beyond this paper's scope, further analysis of other issues related to the AM CS is straightforward with the online interactive maps.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1. ISO/ASTM. Additive manufacturing — General principles — Terminology. International Organization for Standardization, Geneva, Switzerland. 2015.
2. Campbell T, Williams C, Ivanova O, *et al*. Could 3D Printing Change the World? Technologies, Potential, and Implications of Additive Manufacturing. Atlantic Council, Washington, DC 2011;3:1-6.
3. Gibson I, Rosen D, Stucker B. Additive Manufacturing Technologies. Springer New York: New York, NY; 2015. doi: 10.1007/978-1-4939-2113-3.
4. Berman B. 3-D printing: The new industrial revolution. Bus Horiz. 2012;55(2):155-62; doi: 10.1016/j.bushor.2011.11.003.
5. Lee J-Y, An J, Chua CK. Fundamentals and applications of 3D printing for novel materials. Applied Materials Today. 2017;7:120-33; doi: 10.1016/j.apmt.2017.02.004.
6. Gao W, Zhang Y, Ramanujan D, *et al*. The status, challenges, and future of additive manufacturing in engineering. Comput Des 2015;69:65-89; doi: 10.1016/j.cad.2015.04.001.
7. Huang SH, Liu P, Mokasdar A, *et al*. Additive manufacturing and its societal impact: a literature review. Int J Adv Manuf Technol 2013;67(5-8):1191-203; doi: 10.1007/s00170-012-4558-5.
8. Kruth J-P, Leu MC, Nakagawa T. Progress in Additive Manufacturing and Rapid Prototyping. CIRP Ann 1998;47(2):525-40; doi: 10.1016/S0007-8506(07)63240-5.
9. Ngo TD, Kashani A, Imbalzano G, *et al*. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. Compos Part B Eng 2018;143:172-96; doi: 10.1016/j.compositesb.2018.02.012.
10. Thompson MK, Moroni G, Vaneker T, *et al*. Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints. CIRP Ann 2016;65(2):737-60; doi: 10.1016/j.cirp.2016.05.004.
11. Bikas H, Stavropoulos P, Chryssolouris G. Additive manufacturing methods and modelling approaches: a critical review. Int J Adv Manuf Technol 2016;83(1-4):389-405; doi: 10.1007/s00170-015-7576-2.
12. Huang Y, Leu MC, Mazumder J, *et al*. Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations. J Manuf Sci Eng 2015;137(1):1-10; doi: 10.1115/1.4028725.
13. Ford S, Despeisse M. Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. J Clean Prod 2016;137:1573-87; doi: 10.1016/j.jclepro.2016.04.150.
14. Muhammad A, Ali MAH, Shanono IH, *et al*. A systematic and bibliometric analysis on 3D printing published in scientific citation index-expanded indexed journals between 1999 and 2019. Mater Today Proc 2021;44:1739-43; doi: 10.1016/j.matpr.2020.11.902.
15. Zarrabeitia Bilbao E, Rio Belver RM, Alvarez Meaza I, *et al*. Additive manufacturing vs metal additive manufacturing technologies in engineering: a bibliometric and web indicator analysis. Dyna 2020;95(1):364-70; doi: 10.6036/9605.
16. Haleem A, Javaid M. 3D printed medical parts with different materials using additive manufacturing. Clin Epidemiol Glob Heal 2019;8(1):215-23; doi: 10.1016/j.cegh.2019.08.002.
17. Obi MU, Pradel P, Sinclair M, *et al*. A bibliometric analysis of research in design for additive manufacturing. Rapid Prototyp J 2022; doi: 10.1108/RPJ-11-2020-0291.
18. García-León RA, Gómez-Camperos JA, Jaramillo HY. Scientometric Review of Trends on the Mechanical Properties of Additive Manufacturing and 3D Printing. J Mater Eng Perform 2021;30:4724-34; doi: 10.1007/s11665-021-05524-7.
19. Parvanda R, Kala P, Sharma V. Bibliometric Analysis-Based Review of Fused Deposition Modeling 3D Printing Method (1994–2020). 3D Print Addit Manuf 2021; doi: 10.1089/3dp.2021.0046.
20. Wang Y, Mushtaq RT, Ahmed A, *et al*. Additive manufacturing is sustainable technology: citespace based bibliometric investigations of fused deposition modeling approach. Rapid Prototyp J 2021; doi: 10.1108/RPJ-05-2021-0112.
21. Garcia-Garcia LA, Rodríguez M. Competitive and technology intelligence to reveal the most influential authors and inter-institutional collaborations on additive manufacturing for hand orthoses. J Intell Stud Bus 2019;8(3); doi: 10.37380/jisib.v8i3.364.
22. Kusoglu IM, Doñate-Buendía C, Barcikowski S, *et al*. Laser Powder Bed Fusion of Polymers: Quantitative Research Direction Indices. Materials (Basel) 2021;14(5):1169; doi: 10.3390/ma14051169.
23. Ameen W, Ghaleb AM, Alatefi M, *et al*. An overview of selective laser sintering and melting research using bibliometric indicators. Virtual Phys Prototyp 2018; doi: 10.1080/17452759.2018.1489973.
24. Zheng Y, Zhang W, Baca Lopez DM, *et al*. Scientometric Analysis and Systematic Review of Multi-Material Additive Manufacturing of Polymers. Polymers (Basel) 2021;13(12):1957; doi: 10.3390/polym13121957.
25. Dzogbewu TC, Amoah N, Fianko SK, *et al*. Additive manufacturing towards product production: a bibliometric analysis. Manuf Rev 2022;9(1); doi: 10.1051/mfreview/2021032.
26. Nyika J, Mwema FM, Mahamood RM, *et al*. A five-year scientometric analysis of the environmental effects of 3D printing. Adv Mater Process Technol 2021;1-11; doi: 10.1080/2374068X.2021.1945267.
27. Ukobitz DV. Organizational adoption of 3D printing technology: a semisystematic literature review. J Manuf Technol Manag 2021;32(9):48-74; doi: 10.1108/JMTM-03-2020-0087.
28. Matos F, Jacinto C. Additive manufacturing technology: mapping social impacts. J Manuf Technol Manag 2019;30(1):70-97; doi: 10.1108/JMTM-12-2017-0263.
29. Haleem A, Javaid M. Additive Manufacturing Applications in Industry 4.0: A Review. J Ind Integr Manag 2019;4(4):1930001; doi: 10.1142/S2424862219300011.
30. Hernandez Korner ME, Lambán MP, Albajez JA, *et al*. Systematic Literature Review: Integration of Additive Manufacturing and Industry 4.0. Metals (Basel) 2020;10(8):1061; doi: 10.3390/met10081061.
31. Caviggioli F, Ughetto E. A bibliometric analysis of the research dealing with the impact of additive manufacturing on industry, business and society. Int J Prod Econ 2019;208:254-68; doi: 10.1016/j.ijpe.2018.11.022.
32. Li M, Porter AL. Facilitating the discovery of relevant studies on risk analysis for three-dimensional printing based on an integrated framework. Scientometrics 2018;114:277-300; doi: 10.1007/s11192-017-2570-0.
33. Nuñez J, Ortiz Á, Ramírez MAJ, *et al*. Additive Manufacturing and Supply Chain: A Review and Bibliometric Analysis. In: Engineering Digital Transformation 2019:323-31; doi: 10.1007/978-3-319-96005-0_39.
34. Lezama-Nicolás R, Rodríguez-Salvador M, Río-Belver R, *et al*. A bibliometric method for assessing technological maturity: the case of additive manufacturing. Scientometrics 2018;117(3):1425-52; doi: 10.1007/s11192-018-2941-1.
35. Ning X, Liu T, Wu C, *et al*. 3D Printing in Construction: Current Status, Implementation Hindrances, and Development Agenda. Zhang Z. ed. Adv Civ Eng 2021;2021:1-12; doi: 10.1155/2021/6665333.
36. Santoni S, Gugliandolo SG, Sponchioni M, *et al*. 3D bioprinting: current status and trends—a guide to the literature and industrial practice. Bio-Design Manuf 2022;5:14-42; doi: 10.1007/s42242-021-00165-0.
37. Tian G. On Evolution and Development Frontier of 3D Printing Technology Based on Document Analysis. In: Proceedings of the 2017 5th International Conference on Frontiers of Manufacturing Science and Measuring Technology (FMSMT 2017) Atlantis Press: Paris, France; 2017;309-12; doi: 10.2991/fmsmt-17.2017.67.
38. Marinescu (Repanovici) R, Nedelcu A. 3D printing new direction and collaboration in scientific research. A scientometric study using Web of Science, Clarivate Analytics database. Slătineanu L, Merticaru V, Mihalache AM, *et al*. eds. MATEC Web Conf 2018;178:07009; doi: 10.1051/matecconf/201817807009.
39. Rodríguez-Salvador M, Rio-Belver RM, Garechana-Anacabe G. Scientometric and patentometric analyses to determine the knowledge landscape in innovative technologies: The case of 3D bioprinting. Lozano S. ed. PLoS One 2017;12(6):e0180375; doi: 10.1371/journal.pone.0180375.
40. Zarrabeitia-Bilbao E, Álvarez-Meaza I, Río-Belver RM, *et al*. Additive manufacturing technologies for biomedical engineering applications: Research trends and scientific impact. Prof la Inf 2019;28(2):1-21.
41. Galina AC, Leta J. 3D Printing: A Research Domain of Multiple Facets? J Scientometr Res 2020;9(2):111-9; doi: 10.5530/jscires.9.2.14.
42. Bai W, Fang H, Wang Y, *et al*. Academic Insights and Perspectives in 3D Printing: A Bibliometric Review. Appl Sci 2021;11(18):8298; doi: 10.3390/app11188298.
43. Sood S, Rawat K, Sharma G. 3-D Printing Technologies From Infancy to Recent Times: A Scientometric Review. IEEE Trans Eng Manag 2022;1-17; doi: 10.1109/TEM.2021.3134128.
44. Jemghili R, Ait Taleb A, Khalifa M. A bibliometric indicators analysis of additive manufacturing research trends from 2010 to 2020. Rapid Prototyp J 2021;27(7):1432-54; doi: 10.1108/RPJ-11-2020-0274.
45. Jin Y, Li X, Campbell RI, *et al*. Visualizing the hotspots and emerging trends of 3D printing through scientometrics. Rapid Prototyp J 2018;24(5):801-12; doi: 10.1108/RPJ-05-2017-0100.
46. Gupta BM, Dhawan SM. 3D Printing: A Scientometric Assessment of Global Publications Output during 2007-16. DESIDOC J Libr Inf Technol 2018;38(4):238; doi: 10.14429/djlit.38.4.12300.
47. van Eck NJ, Waltman L. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 2010;84(2):523-38; doi: 10.1007/s11192-009-0146-3.
48. R Core Team. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. 2021. https://www.R-project.org/
49. Malone E, Lipson H. Fab@Home: the personal desktop fabricator kit. Rapid Prototyp J 2007;13(4):245-55; doi: 10.1108/13552540710776197.
50. Sells E, Bailard S, Smith Z, *et al*. RepRap: The Replicating Rapid Prototyper: Maximizing Customizability by Breeding the Means of Production. In: Handbook of Research in Mass Customization and Personalization World Scientific Publishing Company; 2009:568-80; doi: 10.1142/9789814280280_0028.
51. Sells E. Towards a Self-Manufacturing Rapid Prototyping Machine. University of Bath; 2009.
52. Jones R, Haufe P, Sells E, *et al*. RepRap – the replicating rapid prototyper. Robotica 2011;29(1):177-91; doi: 10.1017/S026357471000069X.
53. Hull CW. Apparatus for Production of Three-Dimensional Objects by Stereolithography. U.S. Patent No. 4,575,330. Washington, DC: U.S. Patent and Trademark Office. 1986.

54. Feygin M. Apparatus and Method for Forming an Integral Object from Laminations. U.S. Patent No. 4,752,352. Washington, DC: U.S. Patent and Trademark Office. 1988.
55. Deckard CR. Method and Apparatus for Producing Parts by Selective Sintering. U.S. Patent No. 4,863,538. Washington, DC: U.S. Patent and Trademark Office. 1989.
56. Crump SS. Apparatus and Method for Creating Three-Dimensional Objects. U.S. Patent No. 5,121,329. Washington, DC: U.S. Patent and Trademark Office. 1992.
57. Sachs EM, Haggerty JS, Cima MJ, *et al*. Three-Dimensional Printing Techniques. U.S. Patent No. 5,204,055. Washington, DC: U.S. Patent and Trademark Office. 1993.
58. N. Turner B, Strong R, A. Gold S. A review of melt extrusion additive manufacturing processes: I. Process design and modeling. Rapid Prototyp J 2014;20(3):192-204; doi: 10.1108/RPJ-01-2013-0012.
59. van Eck NJ, Waltman L. VOSviewer Manual. 2022;1-53.
60. van Eck NJ, Waltman L. VOS: A New Method for Visualizing Similarities Between Objects. In: In H.-J. Lenz and R. Decker (Eds.), Advances in Data Analysis: Proceedings of the 30th Annual Conference of the German Classification Heidelberg: Springer; 2007:299-306; doi: 10.1007/978-3-540-70981-7_34.
61. van Eck NJ, Waltman L. Text Mining and Visualization using VOSviewer. ISSI Newsl 2011;7(3):50-4.
62. WIPO. World Intellectual Property Report: Breakthrough Innovation and Economic Growth. Econ Stat Ser 2015;1-144.

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