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Research Article

3D Printing: A Research Domain of Multiple Facets?

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ABSTRACT
The 3D printing, a synonym for additive manufacturing, is an emerging technology based on the principle of additive manufacturing, that is, a material deposition in a tiny layer-by-layer process until the designed shape is completed. Considering the history of this technology, its products were at first closer to engineering, whereas more recently its products are diversifying to multiple areas. Hence, the present paper aims to investigate whether this technology figures out as a multi-faceted research domain. A complex search strategy with 41 words was used and 71,537 publications on 3D printing in the 1980-2019 period were found. The set of analysis based on time trend, the main typologies, the top 15 research fields and journal co-citation networks indicate a multiple faceted field trend for publications on 3D printing that goes beyond engineering, computer science and material science, fields where originally this technology matured.

Keywords: 3D Printing, Additive manufacturing, Emerging technology, Research domain, Scientific Publications.

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INTRODUCTION

Emerging technologies are known as those with the potential to create a new sector or to transform an existing one. Also, emerging technologies may be considered as discontinuous technologies derived either from radical innovations or from the convergence of research chains in a variety of fields,[1] including nanotechnology, robotics, artificial intelligence and biotechnology. Based on this concept, in 2015, during the World Economic Forum, held in Davos, Switzerland, a selective group of experts on emerging technologies elaborated a list of the ten most revolutionary technologies, which “offer a vivid glimpse of the power of innovation to improve lives, transform industries and safeguard our planet”.[2] Included in this list was the additive manufacturing process, on which 3D printing technology is based.

Although, the first patents of 3D printing technology were deposited in the middle of 1980’s, a global understanding of its potential as a disruptive innovation as well as its recognition as an emerging technology happened more recently among governments and national institutes. They started formulating strategies to develop and to enhance not only the 3D printing industry but also the industry chain that surrounds it. In fact, one of the first National report to emphasize on it was the “100 opportunities for Finland and the world”,[3] launched in 2014, in which many economic opportunities are related to 3D printing technology, such as 3D printing of goods, 3D printing of buildings, 3D and 4D printing of material and 3D printing of organs.

Some other examples include the report “Made in China 2025”,[4] published by the Chinese State Council in 2015, where the 3D printing technology was listed as one of the priorities to be supported by the first ten-year plan to upgrade the manufacturing industry and the FutureAM,[5] a German project launched by the Fraunhofer Institute and other six partners in 2017, that aimed the development and improvement of 3D printing that produces metallic components.

The 3D printing technology, a synonym for additive manufacturing,[6] is characterized by a process of material deposition in a tiny layer-by-layer, until the designed shape completes. This process differs from the conventional subtractive manufacturing, which is grounded in a technique that removes the material from the block to be formed.[6] Comparing the subtractive and additive manufacturing, the latter is characterized not only by a shorter time of production but also by a lower level of energy and material consumption as well as a lower amount of waste and pollutants. These benefits and others that 3D printing displays when compared to traditional manufacturing processes are widely known and reported.[7,8]

It is striking to highlight the current impact of 3D printing in economy, which is estimated to achieve around US $ 230 to US $ 550 billion per year by 2020.[9] According to Markets and Markets for 2021, the value of 3D printing ceramics materials market is estimated to be US $ 131.5 million.[10] Such impressive impact on economy is also expected to achieve social and work environment once it introduces a new method of production, fabrication and distribution of goods, leading to the emergence of industry 4.0 model that displays higher non-traditional manufacturing capacity and mass customization.[11] In fact, many authors[11,12] consider that 3D printing is about to bring a radical change in contemporary culture due to the advances in manufacturing to produce a large number of products, including customized products, applied to industry, art, medicine and domestic environment. Also, they believe that the improvement and dissemination of 3D printing may bring about changes in the world economy by changing business models, production places and supply chains as well as by shifting work structures.

The impact of 3D printing is already perceived in society through a range of products, including parts to build a house or components to assemble cars and airplanes. Clothes and accessories, household utensils, food and medicines can also be printed / produced with 3D printings.[13] More recently, we witnessed products printed by 3D printing technology that may represent a paradigm shift in the society: the impression of skin, bone, vascular grafts, tracheal splints, cardiac tissue, cartilaginous structures and other human macro-molecules. Such products (and others not yet available) have the potential to radically transform the way and the time spent on medical treatments. In fact, the application of 3D printing to solve health problems, especially those related to human organs, macromolecules and other biomaterials may represent the "next technology revolution for the pharmaceutical and medical-device industries".[14]

Taking into account the current and future uses of 3D printing in generating products that impact science and other social sectors, the present paper aims to investigate whether this technology Figures out as a multi-faceted research domain, that is, their scientific actors share thoughts, discourses and communication forms, among other aspects.[15] In a historical perspective, the 3D printing products were initially related to engineering, while more recently it turned to a wider spectrum of products related to multiple areas. Does the research on 3D printing follow a similar movement of that observed at the market? Do authors of 3D printing scientific publications share a wider literature that could indicate to a multi-faceted research domain at present? Hence, in order to answer these questions, a bibliometric approach, especially based in co-citation analysis, is applied in this paper. In fact, such type of analysis displays "real connections between individual documents. These links represent the authors' explicit acknowledgment of dependency between, for example, papers, researchers, fields, approaches and geographical regions".[16]

Although the technology dates back to the 1980s, few studies on scientometric literature date from the 2000's and cover both patents and publications. Regarding the latter, which is the focus of the present paper, a study published in 2014 makes a large descriptive analysis of 3D printing publications indexed in Web of Science (WoS) database from 1984-2014.[17] In 2018, two other studies have added new information on the world's 3D printing publications. One study analyzed 11,529 documents retrieved from WoS database on 3D printing in Engineering Fabrication field and found both a large geographical coverage, mainly in USA, Europe, Asia, Africa and the prevalence of proceedings papers.[18] The other one has analyzed 7,309 publications on 3D printing indexed in Scopus database during 2007-16 and found similar results on geographical coverage but have also investigated the most prolific authors, institutes and fields.[19]

To our knowledge, the first study on 3D printing research with focus on the concept of research domain was carried out by our group.[20] The set of results presented in our previous study indicated that research on 3D printing was strongly related to engineering, computer science and material science, while health sciences has emerged more recently. The present paper further enriches our previous study by (i) re-examining the search strategy and the periods of analysis, which are better detailed in methodology, (ii) considering data extracted only from Scopus database that reduced the number of examined documents but increased the reliability of data and (iii) including the list of the top 15 research fields as well as a journal co-citation analysis within the two main document typologies. These changes have enabled the identification of a multiple faceted field trend for publications on 3D printing that goes beyond the ones observed previously.

Methodology

The search strategy included three main steps. The first search strategy contained a couple of words found in articles and news about 3D printing plus some synonyms listed in MESH terms,[21] and their variations. Then, based on the results of the first strategy, a co-occurrence analysis of keywords was performed, which allowed the identification of other words and terms related to the use of 3D printing technique in specific areas, for example, bioprinting. Finally, words and their variations regarding the seven additive manufacturing families listed in ISO / ASTM 52900: 2015, or formerly ASTMF 2792[22,23] were added to the search.

These steps were presented in our previous study[20] and, at the end, 44 words were included in the search strategy. Nevertheless, after consulting a 3DP expert, the search strategy was reviewed and the number of words was reduced to 41. Among the excluded words was "rapid prototyping", which does not describe exclusively the 3D printing or additive manufacture. Considering these changes, the revised search strategy, including 41 words, as following: "Electron Beam Melt*" OR "Material Jet*" OR "Multi-Jet Fus*" OR "Binder Jet*" OR "Ultrasonic Additive Manufactur*" OR "Voxeljet" OR "Drop On Demand" OR "Nano Particle Jet*" OR "Polyjet" OR "Sheet Laminat*" OR "Laminat* Object Manufactur*" OR "Selective Deposit* Laminat*" OR "Electron Beam Additive Manufactur*" OR "Laser Metal Deposit*" OR "Direct Metal Deposit*" OR "Bioplot*" OR "Bioprint*" OR "Bio-print*" OR "Material Extrusion" OR "Fused Deposition Model*" OR "Fused Filament Fabricat*" OR "Directed Energy Deposit*" OR "Laser Engineer*" OR "Net Shap*" OR "Digital Light Process*" OR "Continuous Liquid Interface Production" OR "Continuous Digital-Light Process*" OR "Selective Laser Sintering" OR "3D print*" OR "Threedimensional print*" OR "Three dimensional print*" OR "3 dimensional print*" OR "Solid Free Form" OR "Solid Freeform" OR "Additive Manufacturing" OR "VAT Photopolymerisation" OR "Stereolithography" or "ExOne" OR "Powder Bed Fusion" OR "Direct Metal Laser Sinter*" OR "Selective Laser melt*".

The search strategy was applied to the filter of "title, abstract and keywords", considering all types of documents indexed by Scopus database. The choice of Scopus is due to higher journal coverage when compared to Clarivate/Web Of Science (in a previous study of our group,[20] we have shown that Scopus documents on 3D printing corresponded to more than 75% of total analyzed documents).

The revised search strategy, carried out on December 01st, 2019, resulted in 71,537 documents published in the period 1980-2019, but only 67,584 were retrieved indeed. We have repeated this process but the difference between found and retrieved documents persisted. The non-retrieved documents, which represent 5.5% of the total, are classified as articles.

The analysis of research area considered the 71,537 documents and was obtained directly from Scopus website, filtering by articles and conference proceedings.

In order to visualize changes over time, the analysis are presented in three periods, 1980 - 2004, 2005 - 2009 and 2010 – 2019, which refer to different growth rates, calculated by the curve sloping. The reasons for such time cohort include the fact that it may reveal whether (or not) field trends vary within the growth waves and that any other time cohort would present an unbalancing in terms of number of documents, since most of documents on 3D printing were published after 2010.

Out of 67,584 retrieved documents 64,522 are classified as articles and conference proceedings. The latter total was the basis for journal co-citation analyses, which were performed with the help of VOSviewer 1.6.11[24] and preceded by a cleaning/standardizing stage. The maps include journals or conference proceedings with five or more occurrences/citations. The visualization displays total strength link.

RESULTS

The results are presented in three sections. The first section focuses on the growth of scientific production on 3D printing and its distribution according to the types of document. We think that this first section is necessary to better contextualize the following two sections, which display the central analysis of our study. The second section presents the most prevalent research fields, while the third section shows the journal co-citation analysis.

Growth and typology of scientific publications on 3D printing

The number of documents on 3D printing (blue line) as well as the number of total documents indexed by Scopus (orange line) in the studied period is shown in Figure 1.

In the whole period, Scopus total documents have increased from 652,688 to 3,109,662, while Scopus documents on 3D printing have increased from 42 to 14,418; the average annual growth rates were 4% and 16%, respectively. We can distinguish for 3D research papers three waves: a first wave with a very slow growth up to 2004, a second wave with low growth from 2005 to 2009 and a third one starting in 2010 with an exponential growth.

A recent study has also observed a wave of growth when they analyzed the 7,309 world's publications on 3D printing: 2007-2011 and 2012-2016.[19] Another study, developed by Marinescu and Nedelcu,[18] did not explore the waves of growth but the results suggest at least three periods of distinct growth for the 11,529 world publication 3D printing in the field of Engineering Fabrication: 1983-2006, 2007-2013 and 2014-2018. The difference between the findings of these previous studies and Figure 1 is maybe due to the number of total publications retrieved from the database. Nevertheless, it is worth to highlight that in these two previous works as well

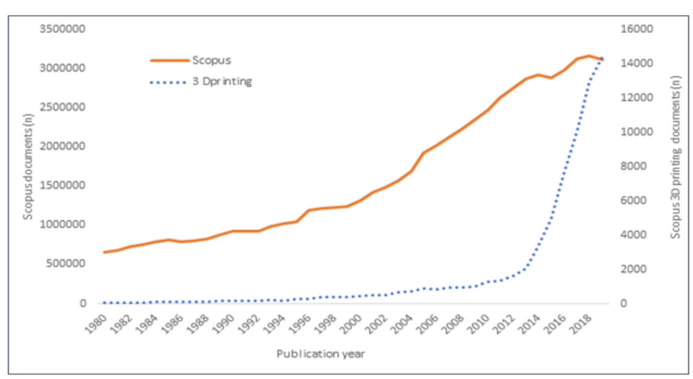

Figure 1: Scopus total number of documents (orange line) and 3D printing documents (blue dot line), 1980-2019.

as in the present one, it has been observed to have outstanding growth in more recent years.

Once the previous results revealed such outstanding increase of publications on 3D printing, an analysis of the prevalent types of documents within the three periods of growth was proceeded in order to get the first evidences of how this domain is structured in terms of means of diffusion.

In Table 1, it can be observed that article is the most frequent typology in all periods among documents on 3D printing, varying from 53% to 63%. The second one is conference proceedings, varying from 31% to 43%. The sum of all other typologies varies from 1.7% to 4.9%.

Table 1: Number of documents on 3D printing according to the typology and period of publication.

Period	Total Documents	Article (%)	Conference (%)	Other types (%)
1980 - 2004	5,761	63.4	34.9	1.7
2005 - 2009	4,444	53.6	43.5	2.9
2010 - 2019	57,379	63.2	31.9	4.9
Total (1980-2019)	67,584	62.6	32.9	4.5
Total found (1980 – 2019)	71,537	64.3	31.2	4.5

Source: Scopus

A similar result was found by Gupta and Dhawan,[19] who state "54.28 per cent appeared as articles, 33.90 per cent as conference papers". Differently, Marinescu and Nedelcu[18] found that "proceedings papers were predominant in 3D printing research", a trend that is in accordance with bibliometric literature, in which conference proceedings are the most common means of communication, especially in fields such as engineering, since it speeds the diffusion of the new knowledge or of the new technology, thus guaranteeing faster priority of the discovery or invention. The prevalence of these two document typologies, articles and proceedings, indicates that authors of 3D printing publications do share different strategies to diffuse their research, suggesting that they probably come from different fields, which are analyzed by different approaches, as following.

Main fields of 3D printing scientific publications

In this section, the main fields of the publications are estimated by analyzing the top 15 main research fields of with the highest percentage of articles and conference proceedings in each period of growth (Table 2). It is worth to highlight that data were collected directly from Scopus main webpage and the analysis considers the total number of documents indexed in the database (n = 71,537).

A general observation is that the field trends among articles and conference proceedings do not differ in terms of the top three research areas, but the comparison between both typologies presents relevant differences in fields with intermediate or low percentage share.

Regarding articles, the top three main research fields are Engineering, Material Science and Physics and Astronomy. But although these fields keep their position ranks along the periods, it is clear that Engineering and Material Science articles lost importance in recent periods due to the strong reduction in the percentage share they represent. In an opposite direction, Medicine and Biochemistry, Genetics and Molecular Biology gained importance among 3D printing publications, once they display an impressive increase in terms of share and position rank.

It is important to highlight the increase of articles in the field of Dentistry, even though it did not represent a shift in the ranking position. This tendency reinforces the increasing interest within research on 3D printing for health related aspects.

As for conference proceedings, Engineering and Material Science are the top two research fields during the studied periods, while Physics and Astronomy appears in 3rd position, except in the last period. Documents from these fields also seem to be losing importance, especially those from Engineering. The predominant role of Engineering and Material Science was also observed in the study carried out by Marines cu and Nedelcu.[18] In this case, it was an expected result since the analysis has considered only 3D printing publications in the field of engineering fabrication.

Different from articles, most research fields of conference proceedings has oscillated quite a lot along the periods, not allowing the identification of a growth trend (negative or positive). The exceptions are Computer Science and Medicine, in which we found an increase in the percentage and a shift to a higher rank position. It also calls for attention of the presence of this typology, but not articles, in the fields such as agriculture and biological sciences, social sciences and arts and humanities and health professionals.

The distribution of research fields presented in Table 2 indicates that 3D printing is a research domain that goes beyond the walls of engineering laboratories, embracing also research in fields known as "hard sciences" as well as "soft sciences". This is a clear indication that the global scientific community from a broader and diverse spectrum of fields is concerned with and develops research on 3D printing. A similar result was found by Gupta and Dhawan,[19] when investigating 7,309 world's 3D printing publications, published in the period 2007–16.

Table 2: Research fields of articles and conference proceedings on 3D printing, according to the publication period.

	Articles						Conference Proceedings					
	1980-2004		2005-2009		2010-2019		1980-2004		2005-2009		2010-2019	
Research Field	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank
Engineering	70,6%	1	65,2%	1	59,0%	1	87,8%	1	66,0%	1	67,0%	1
Materials Science	55,6%	2	52,3%	2	42,0%	2	42,0%	2	56,6%	2	33,3%	2
Physics and Astronomy	22,2%	3	24,3%	3	23,9%	3	23,6%	3	39,6%	3	27,8%	4
Computer Science	12,0%	4	13,3%	4	10,8%	5	22,1%	4	20,9%	4	33,0%	3
Chemistry	6,2%	5	9,2%	5	10,3%	7	1,0%	10	1,2%	11	1,8%	12
Chemical Engineering	5,0%	6	8,3%	6	10,2%	8	4,0%	7	4,6%	6	2,9%	8
Medicine	4,2%	7	6,6%	7	11,8%	4	0,9%	11	1,8%	9	3,1%	7
Business, Management and Accounting	3,5%	8	4,2%	9	2,2%	13			0,4%	14	1,4%	15
Mathematics	2,8%	9	3,3%	10	3,4%	10	14,4%	5	8,1%	5	12,9%	5
Biochem, Genetics and Molecular Biol	1,3%	10	5,2%	8	10,5%	6	0,5%	12	2,2%	7	1,4%	14
Dentistry	1,2%	11	1,8%	11	2,5%	11						
Energy	1,1%	12	1,1%	14	2,1%	14	1,7%	9	1,1%	12	4,7%	6
Earth and Planetary Sciences	0,8%	13	1,4%	12	7,5%	9	2,0%	8	1,9%	8	2,5%	9
Environmental Science	0,7%	14	1,1%	15			5,7%	6	1,6%	10	2,1%	11
Decision Sciences	0,5%	15							0,4%	14	1,7%	13
Pharmacol, Toxicol and Pharmaceutics					2,3%	12						
Multidisciplinary			1,3%	13	2,0%	15						
Social Sciences							0,4%	13	0,3%	15	2,3%	10
Agricultural and Biological Sciences							0,1%	14				
Arts and Humanities							0,1%	15				
Health Professions									0,6%	13		

Source: Scopus

Intellectual structure of 3D printing scientific publications

In order to get additional data for better understanding of how research on 3D printing is structured in terms of field, we have carried out a journal co-citation analysis considering the two main document typologies. This technique was first proposed by McCain[25] and it has the premise that the greater is the frequency of pairs of references cited simultaneously in a third study, the closer is the relationship between the pairs of references. Thus, the journal co-citation analysis allows identifying clusters of journals that share themes and interests, revealing, as many authors have indicated,[26-28] the intellectual structure of the publications.

A summary of the main network parameters obtained through journal co-citation data extracted from 3D printing articles

Table 3: Journal co-citation network parameters based on data extracted from 3D printing articles and conference proceedings.

ARTICLES	1980 - 2004	2005 – 2009	2010 - 2019
Cited journals	16,224	13,339	178,611
Cited journals with ≥5 citations	789	784	17,353
Connected cited journals	782	779	17,347
Number clusters	12	20	44
CONFERENCE PROCEEDINGS	**1980 - 2004**	**2005 – 2009**	**2010 - 2019**
Cited journals	5,550	8,506	92,313
Cited journals with ≥5 citations	218	373	4,894
Connected cited journals	215	367	4,882
Number clusters	12	14	28

Source: Scopus

and proceedings, respectively, in each of the three studied periods, is presented in Table 3. A general observation is that the values of all parameters observed for the networks of co-cited journals in articles are much higher than that observed in proceedings. Such difference is probably related to both the difference in the share of articles and proceedings (Table 1) and the less number of cited references normally found in conference proceedings.

Figures 2A, 2B and 2C present the journal co-citation network extracted from articles on 3D printing published in one of the three studied periods. A first observation is that the maps gain density along the periods, since there is an increase in the number of both clusters (in different colors) and journals (as nodes).

We also observe that only five (or four) clusters concentrate more than 80% of connected cited journals. Thus, we focused the analysis in these clusters.

Regarding the period 1980-2004 (Figure 2A), the red cluster (with 256 nodes), the dark blue (with 111) and the purple (with 54) are clearly related to Engineering and Material Science research on production, manufacturing and processes, embracing journals as: Proc. solid. Free form fabricate., j. rapid. Proto type., j. mat. proc. technol. and cirp ann. manuf. technol. in red cluster; Mater. sci. eng., scripta mat., metall. trans. and acta metall. mat. in dark blue cluster; and j. mat. sci., mat. trans. jim., jom, int. j. rapid solicif., int. j. powder met., j. metals in purple cluster. The yellow cluster (with 68 nodes) reinforces the predominance of exact sciences in the co-cited journal structure once it contains journals related to Physics, such as: j. app. phys., appl. phys.lett, phys. rev. lett. and phys. rev. Finally, the green cluster (with 146 nodes) displays a mixed field tendency: it encompasses generalist journals such as Science and Nature, but also journals related to subjects and applications in Health sciences as j. biomed. mat. res., biomat. sci., j. dente. res. and tissue eng.

As for the period 1980-2004 (Figure 2B), we found that only two clusters are related to Engineering and Material Science, the red (with 198 nodes) and the yellow (with 94 nodes), including journals as: j. rapid prototyp., j. mat. proc. technol., proc. solid freeform fabricate. and mat. Design in red cluster; and mater. sci. eng. scripta mat., acta metall. mat., jom and metall. trans. in yellow cluster. The blue cluster (with 151 nodes) has shifted its field tendency to a broaden one, including generalist journals, such as Nature, but also journals from Physics and Chemistry, as appl. phys., j. app. phys.,appl. phys. lett., adv. mat. and lagmuir. The green cluster (with 173 nodes) is more clearly related to applications in Health sciences, including two giant nodes (biomat. sci. and j. biomed. mat. res.), which are highlighted in Figure 3B inset. Co-cited journals related to Health sciences and Biomedicine are also presented in the purple cluster (with 43 nodes), including: j. control. release, trends biotechnol., adv. drug. deliv. rev., nat. mat., j. pharm. sci. and j. biomater. sci.

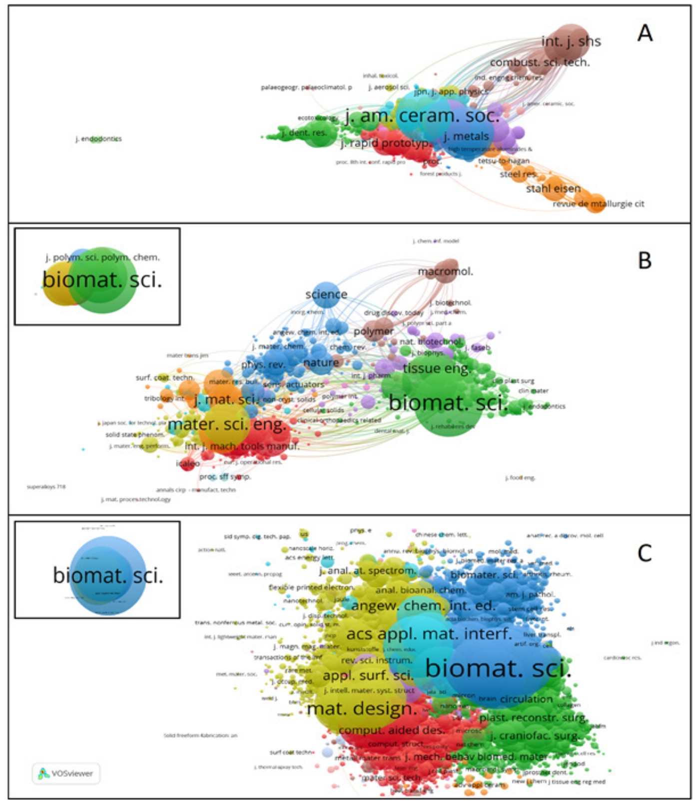

Figure 2: Journal co-citation network of articles on 3D printing retrieved from Scopus in 1980-2004 (A), 2005-2009 (B) and 2010-2019 (C).

Considering the most recent period, 2010-2019 (Figure 2C), we found that only four clusters concentrate 88% of co-cited journals. As previous period, red (with 7,515 nodes) and yellow (with 2,174 nodes) clusters retain journals related to Engineering and Material Science, including a giant node with the following journals: j. rapid. prototyp., j. mat. proc. technol. and int. j. adv. manuf. technol in red cluster and mater sci. eng., mat. design. and acta metall. mat. in yellow cluster. The two other clusters are devoted to Health sciences, being the green one (with 3,262 nodes) strongly related to Orthopedics and Dentistry, including journals as: plast. reconst. surg., clin. orthop., j. craniofac. surg., j. prosthet. dente., int. j, pharm., j. oral maxillofac. surg., clin. orthop., circulation, j. orthop. res. and stem cells. As for the dark blue cluster (with 2,174 nodes), it displays a giant node with journals as biomat. sci., tissue eng., biofabricat., acta biomat., nature, sci. rep. and lab a chip., which, with the exception of Nature, are devoted to subjects and applications in Health sciences.

As a final analysis, Figures 3A, 3B and 3C present the journal co-citation network extracted from conference proceedings on 3D printing published in one of the three studied periods.

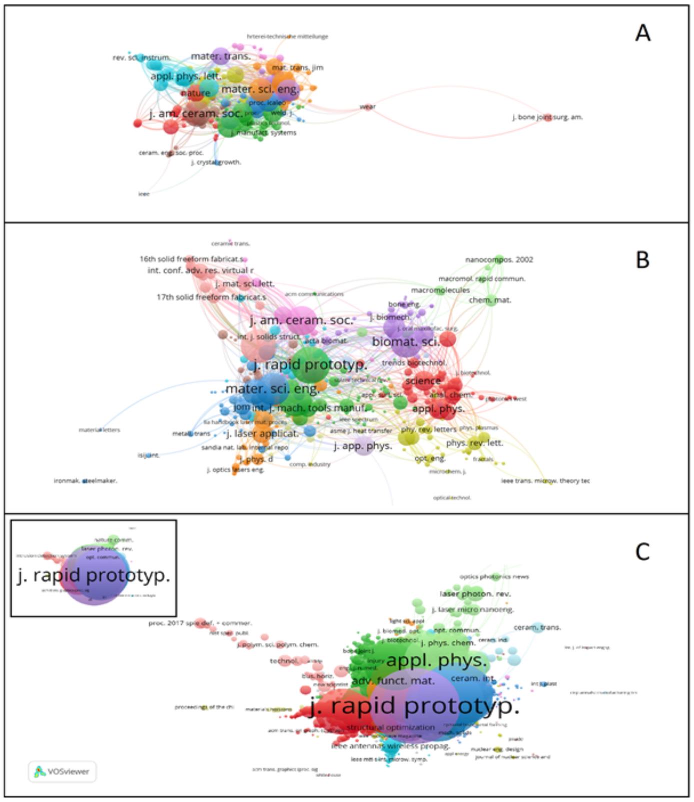

Figure 3: Journal co-citation network of conference papers on 3D printing retrieved from Scopus in 1980-2004 (A), 2005-2009 (B) and 2010-2019 (C).

Compared to previous analysis, the maps based on cited journals from proceedings do also display an increase in density along the periods, but in a more linear rate. On the other hand, we found that up to eight main clusters concentrate more than 80% of connected cited journals, indicating a more dispersed intellectual structure.

For the period 1980-2004 (Figure 3A), we observed that four out of seven main clusters are related to Engineering and Material science: green (with 32 nodes), dark blue (31 nodes), purple (22 nodes) and orange (20 nodes). The most frequent journals encompassed in these clusters are: j. rapid prototyp., proc. solid freeform., fabricat. and j. mat. proc. technol. in green; Jom, j. mat. sci., mat. design. and j. laser applicat. in dark blue; metall. trans., int. j. powder met., j. metals, mat. sci. technol. and mater. trans in purple; and mater. sci. eng., acta metall. mat. scripta mat. and mater. sci. forum. in orange cluster. The light blue cluster (with 21 nodes) is clearly related to the field of Physics and its the most frequent journals are j. appl. phys., phys. rev. and appl. phys. lett. The red cluster (with 34 nodes) and the yellow one (with 22 nodes) are miscellaneous. The first includes journals related to Ceramics, that is, Material Science as well as to Medicine and a generalist journal, they are: j. am. ceram., j.euro. ceram. soc., Sens. actuators, nature, j. bone. surg. am., Wear. The other cluster includes journals associated to Physics, Material science and also to applications in Health sciences, they are: appl. phys., biomat. sci., science, tissue eng., j. biomed. mat. res. and j. mat.res.

Regarding the period 2005-2010, we did not find any significant change in comparison to the previous period, but a spread in the number of clusters that hold 80% of co-cited journals. Clusters related to Engineering and Material science are also prevalent: green (with 49 nodes), dark blue (43 nodes), light blue (31 nodes) and brown (17 nodes). The yellow (with 35 nodes) and the purple (with 43 nodes) clusters hold co-cited in the field of Physics, especially Optics (as proc. spie and phy. rev. letters.) and applications in Health science (as biomat. sci., j. biomed. mat. res. and tissue eng.). Other two clusters, red (with 58 nodes) and orange (28 nodes), hold co-cited journals from different fields, as following: Science, Adv. mat., Appl. phys. Langmuir, Appl. phys. lett and nature in the red cluster and metall. trans., j. laser applicat., j. phys. d., wear, app. surf. sci. and thin. solid. films. in the orange cluster.

Considering the last period, we found two fields main groups: one including four clusters clearly related to Engineering and Material science and another one with two clusters related to multiple fields, that is, miscellaneous. The first group includes the dark blue cluster (with 645 nodes), yellow (547 nodes), purple (379 nodes) and light blue (373 nodes), embracing tow giant nodes with journals as: j. mat. proc. technol., mater sci. eng. and mat. design in dark blue cluster and j. rapid. prototyp. Others: addit. manuf., cirp ann. manuf. technol., phys. procedid., compos. partes., virtual phys. prototyp.,cirp procedia and the int. j. adv. manufact. As for the miscellaneous clusters, we found the red cluster (959 nodes), green (938 nodes) and orange (324 nodes). We found co-cited journals related to Computer science (as acm trans. graph. and comput. aided des.), Engineering (as j. mech. Design) and applied Mathematics (as struct. multidiscip. optim.) in the red cluster; also to Health sciences (as biomat. sci. and tissue eng.) and to Physiscs (as appl. phys., j. appl. phys., opt. express.); and to Material science (as adv. mat. and adv. funct. mat.), Chemistry and Physics (sens. actuators, lab a chip) and generalist (sci. rep. and science).

CONCLUSION AND FINAL REMARKS

3D printing is an emerging technology, with a great economic potential and which has been incorporated into the routine of various social sectors. There is a great expectation that this technology will introduce several changes in society, including in the production chain, since it allows the consumer to print (or produce) his own product, among other features.

Despite the growing interest in this technology, studies in the field of Scientometric or Bibliometric on 3D printing scientific production are relatively scarce or even non-existent if we consider the focus of the present study that is grounded in the research questions: Does the research on 3D printing follow a similar movement of that observed in the market? Do authors of 3D printing scientific publications share a wider literature that could indicate to a multi-faceted research domain at the present? In order to answer these questions, the present study considered a very complex and exhausted search strategy with 41 words, while similar works[18,19] have used simpler search strategies with few words.

Considering the main results, we noted a remarkable growth of 3D printing publications, especially in the last studied period, where we found an exponential growth of publications. Previous studies[17-19] have also detected outstanding growth during the 2000's. Such impressive growth observed for the 3D printing publications may have been pushed by events and initiatives that promoted and spread globally the concept of 3D printing, including: (a) the release of the first open source 3D printer named Darwin by Riprap project in 2007 (b) the launch in internet of the RepRap community in 2008, which began to teach, through free videos, how to assemble a low-cost 3D printings, (c) the foundation of the Thingiverse site, the first dedicated to share files for 3D printing using open source hardware [28], (d) a patent breach in 2009 of the fused deposition modeling (FDM) technique, which allowed the launch of the first desktop 3D printing in 2012 and (e) the foundation of MakerBot that makes available kits to set up homemade 3D printers.

We have also observed that more than 90% of 3D printing publications was classified under the typologies of articles and conference proceedings. It is important to highlight the share of conference proceedings within the total 3D printing publications (around 33%). It is well documented that proceedings are the most common means of research communication in fields as engineering and exact sciences, since it speeds the diffusion of new knowledge or technology, guaranteeing, in a more quick way, the priority of the discovery or invention.

This first observation corroborates the findings for fields (Table 2, Figure 2 and Figure 3), in which we found that Engineering, Physics and Material Science were the most prevalent research fields in both 3D printing publications and their intellectual structure. It is important to highlight that this was the result which was previously presented by our group.[20] Nevertheless, in this current study, we have also detected a great diversity of research fields among publications on 3D printing, including not only Health Sciences, but a broader spectrum of scientific fields from exact sciences to humanities and social sciences. From Table 2, we can clearly observe such diversity.

Considering the time trends, the most relevant finding is related to the increasing presence of Health sciences, mainly Medicine in both articles and conference proceedings and Biochemistry, Genetics and Molecular Biology in articles only (Table 2). A stronger presence of Health sciences was also observed among co-cited journals from more recent articles on 3D printing, but not from proceedings (Figures 2 and 3). This recent shift in the trend of the 3D printing research field towards health science and related fields seems to be in accordance with the moviment of market in recent times: the application of this technique in several health services, such as transplants, thus having a direct impact on society, with the reduction of cost of products from pharmaceutical industries and medical services.[14] The most disruptive and promising face of 3D printing applications include the bioprinting of organs and tissues to help (a) preoperative planning and surgical treatment, (b) permanent non-bioactive implants, which are mostly used in dentistry and orthopedics, (c) local bioactive scaffolds and (d) printed organs with complete life functions.[29] Hence, our findings point to 3D printing research as domain of multiple facets, comprising publications associated mostly to Engineering, Material Sciences and other fields from exact sciences as well as to Heath Sciences and some related fields, as Biochemistry, Genetics and Molecular Biology, that gained importance in recent times and to other minor fields from exactly and social sciences. The time trend analysis suggests that this scenario of multiple and diverse fields follows the historical perspective of the 3D printing technology, in which we witnessed an increasing movement and interest of commercial products coming first from exact sciences, mainly Engineering and in more recent times from multiple areas, notably Health Sciences.

The study underscores the importance of designing an exhaustive search strategy and applying analytical tools that can help to highlight the key facets of research in this ever growing important field of 3D printing. There are however some limitations of the study that may influence some aspects of the finding. The first one has to do with the inclusion of publications published in 2019. As the data extraction was processed in December 2019, it is expected that more documents would be indexed. The second one is related to the software Vos viewer that does not illustrate clearly networks with more than 1000 items, as Figure 2C and Figure 3C. This technical problem makes it difficult to visualize details of the maps and their clusters. Despite these general limitations, our paper presents relevant data on the field configuration of 3D printing research, a strategic and revolutionary technique that has assumed importance not only in society as a whole, but also within the scientific environment.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ABBREVIATIONS

MESH: Medical Subject Headings; **ISO / ASTM:** International Organization for Standardization / American Society for Testing and Materials.

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