Mapping and prospective of additive manufacturing in the context of Industry 4.0 and 5.0

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Abstract

Purpose – This study aims to investigate the scientific impact of additive manufacturing in recent years, considering its evolution as an Industry 4.0 technology and also in the current context of Industry 5.0. For this aim, advanced statistics and scientometric tools have been used.

Design/methodology/approach – This study aims to explore the trends and impacts of additive manufacturing, focusing on its evolution and its relationship with Industry 4.0 and 5.0. For this purpose, a scientometric study and a meta-analysis of data extracted from the scientific Scopus database have been carried out. R programming and specific bibliometric software have been used to conduct the research. Initially, the data were evaluated from various perspectives, including sources, topics and impact indexes, to assess trends derived from the volume of publications, the impact of sources and affiliations, as well as the production segmented by country and the relationships between authors from different countries. Subsequently, a meta-analysis on keywords has been carried out using two distinct clustering methodologies: link strength and fractionalization. The results obtained were compared to establish a specific taxonomy of the AM subtopics, considering AM as a single body of knowledge related to Industries 4.0 and 5.0 paradigms. The analyses carried out have shown the impact and strong evolution of additive manufacturing as a field of knowledge at the world level, both from the point of view of manufacturing processes and from the point of view of materials science. In addition, some differences have been detected depending on the country. As a result of the meta-analysis, four different subtopics have been detected, some of which are highly related to other technologies and approaches in Industries 4.0 and 5.0 paradigms. Additionally, it establishes a comprehensive taxonomy for AM research, serving as a foundational reference for future studies aimed at exploring the evolution and transformative impact of this technology.

Findings – The analyses carried out have shown the impact and strong evolution of additive manufacturing as a field of knowledge at the world level, both from the point of view of manufacturing processes and from the point of view of materials science. In addition, some differences have been detected depending on the country. As a result of the meta-analysis, four different subtopics have been detected: one of them directly related to the use of recently developed Industry 4.0 technologies in additive manufacturing. The results provide a starting point for prospective studies to understand the evolution and disruption of this technology.

Originality/value – The paper is original and is based on data systematically extracted from scientific databases. Then, a specific methodology based on different advanced tools was applied for scientometric evaluation and meta-analysis.

Keywords Additive manufacturing (AM), Manufacturing, Industry 4.0, Meta-analysis, Bibliometric analysis

Paper type General review

1. Introduction

Rapid prototyping or additive manufacturing (AM), sometimes referred to as 3D printing, has been used for many years. Charles W. Hull of 3-D Systems Corporation developed the first functional 3D printer in 1984.

In the past few years, companies have used AM and are beginning to discover business benefits from the implemented investment (Yong *et al.*, 2020). Currently, AM technology is ripening and has penetrated different markets. It is now used in both prototyping and distributed manufacturing, helping future users adopt AM. The technology is gradually making a

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comeback as a useful tool for increasing internal productivity. It is now one of the most popular and incipient developments in the world of design and marketing today (Attaran, 2017).

At first, the technology was prohibitively pricey and out of reach for the average consumer. But as the 20-first century went on, prices came down, allowing 3-D printers to penetrate numerous specialized industries like transport (Nichols, 2019), construction (Bos *et al.*, 2016),healthcare (Giordano, 2019) and even food (Sun *et al.*, 2015) and creative industries (Abisuga and de Beer, 2023).

Rapid prototyping, direct digital manufacturing, layered manufacturing, and additive fabrication are only a few of the technologies that make up AM. The first use of AM is for rapid prototyping, which accelerates time to market and innovation. Similar functionality may be found in the majority of commercial 3-D printers, which convert drawings into three-dimensional objects using computer-aided design (CAD) (Attaran, 2017).

As it is well known, a three-dimensional object can be manufactured from a digital model using AM, which has become commonplace in recent years with 3D printers widely available and new modelling methods (Tang *et al.*, 2023). However, its industrial applications are still evolving alongside its expansion to non-specialized uses, as AM is a key component of Industry 4.0. This framework describes a methodology to shift from machine-dominated manufacturing to digital production (Oztemel and Gursev, 2020). Furthermore, AM may be integrated with other Industry 4.0 technologies, such as artificial intelligence (AI) or big data (Rodríguez-Martín *et al.*, 2022).

There are several types of AM technologies, each with a specific application in mind (Muthe *et al.*, 2022). There are different additive technologies, and it is often a mistake for non-experts to think that material extrusion technology is the only additive technology. The taxonomy of AM should be internationally codified for greater accuracy and traceability in product and process documentation. So, the ASTM standard F2792 (ASTM, 2012) and ISO/ASTM 529000:2015 (International Organization for Standardization (ISO), 2022), 3D Printing or AM technologies are classified into seven categories and different technologies can be included within each category (Lee *et al.*, 2017):

1 *Material Extrusion:* "Material is selectively dispensed through a nozzle or orifice". Within this category is Fused Deposition Modelling (FDM).
2 Material Jetting "Droplets of build material are selectively disposed". Within this category are Sratsys Polyjet, D3 Systeem's Multijet Printing (MJM), and Solidscape.
3 Blinder Jetting "A liquid bonding agent is selectively deposited to join powder materials". Within this category are Vozeljet, ExOne, and Colour Jet Printing (CJP).
4 Sheet lamination "Material sheets are bonded to form an object". Within this category are Laminated Object Manufacturing (LOM), MCor's A4 Paper Printin,g and Jira'Paper Lamination Technology (PLT).
5 Vat Photopolimerisation "Liquid photopolymer in a vat is selectively cured by light-activated polymerisation". Within this category are Stereolitography (SLA) and Digital Light Processing (DLP).
6 Powder bed fusion "Thermal energy selectively fused regions of a powder bed". Within this category are Selective Laser Sintering (SLS), Selective Laser Melting (SLM) and Electron Bil Melting (EBM).
7 Directed Energy Deposition "Focused thermal energy is used to fuse materials by melting as the material is deposited". Within this category is mainly Laser Engineered Net Shaping (LENS).

Some authors also included in this taxonomy the Directed Energy Deposition (Flynn *et al.*, 2016), using this definition: *"Focused termal energy is used to fuse materials by melting as the material is deposited"* (Champagen, 2007).

Additive manufacturing (AM), recognized for its innovative layer-by-layer production approach, is increasingly seen as the last revolutionary advancement in the manufacturing industry (Ahuja *et al.*, 2015). Additive manufacturing has gained additional recognition and divulgation with rapid prototyping, 3D printing, free-form fabrication, and additive layer manufacturing due to the diversity of its printing materials, additive processes and technologies, and field applications (Rodríguez-Martín *et al.*, 2023).

However, the development of AM is a complex issue since various production-related issues, such as product needs, process management, data management, intellectual property, workflow management, quality assurance, resource planning, etc. are critical matters for AM (Ahuja *et al.*, 2015).

Moreover, AM market trends are rapidly evolving, covering areas such as product lifecycle, optimization, sustainability, waste reduction, and localized manufacturing. The development of AM can also be influenced by topics such as process monitoring, design complexity, process standardization, multi-material and hybrid fabrication, and novel material development, amongst others (Rodríguez-Martín *et al.*, 2023) Within manufacturing, Industry 4.0 enhances process flexibility, enabling the creation of customized products across various sectors and applications. Many of the mentioned topics are directly related to the paradigm of Industry 4.0 since in AM, there can be several different tools for digitalization, such as tagging technology, the Internet of Things (IoT), data transfer, information in Industry 4.0, and intelligent features.

Also, the relationship between AM and new modelling methods (Tang *et al.*, 2023) is important in the context of Industry 4.0 and digitalization.

Industry 4.0 has nine pillars (Parvanda and Kala, 2023). Big data analytics helps make real-time decisions by collecting data at different stages of a product, resulting in product quality optimization and better services **(Chun** *et al.*, 2019**)**. Additive manufacturing is a revolutionary technology that enables organizations to produce complex and customized profiles per need and demand. The industrial Internet of Things (IoT) can integrate all the machines centrally (Almada-Lobo, 2016).

Real-time data about location, performance, feedback, etc. can be collected over the network, and monitoring can be done. Cloud computing provides cloud storage for storing and managing data. It forms the root of technologies like IoT, ML, and AI. Cloud technologies result in effective communication and coordination through cyber-physical systems. Augmented Reality (AR) still in the development stage, but it provides users with real-time information that improves decision-making and workflow. The AR support systems have various capabilities, like sending information and repair instructions to user devices like mobile and PCs in machine breakdown (Zhang and Kwok, 2018). Simulation is the ability of a system to have a virtual run before experimenting. The other term in this regard (Ivanov *et al.*, 2019) is Digital Twin, a virtual prototype of a physical part. The simulation saves time, eliminates errors, and improves product quality. Cybersecurity is an important aspect of the modern production system; gone are the days when operation management systems were closed and unconnected, even though such systems still exist. But to cope with Industry 4.0, communications and information sharing must be done following the standard protocols. Cybersecurity performs the critical operation of saving confidential data and protecting it from cybercrime, resulting in secure and reliable connections. System integration is of two types: horizontal and vertical. Horizontal integration is the coordination among employees at the same level, while vertical integration is the effective communication and coordination from top-level management to shop floor workers. Also, many organizations are not integrated with their vendors, suppliers, customers, etc.; in Industry 4.0, organizations are to be inter- and intra-connected through IT systems and networks. The third industrial revolution introduced robotics and automation, leading industries to use them for complex, repetitive, assembly, and other operations. Autonomous robots provide more flexible operations and are more cooperative (Lennon Olsen and Tomlin, 2019). They can interact with humans and, moreover, learn from them. Therefore, to cope with the modern world's needs and requirements, the adoption of Industry 4.0 pillars is very much required for firms.

The concept of Industry 5.0 acknowledges the industry's potential to achieve social objectives beyond just employment and growth. It aims to transform into a resilient provider of prosperity, ensuring that production respects the limits of our planet while prioritizing the well-being of industry workers at the core of the production process (Breque *et al.*, 2021). Note that the difference with the 4th industrial revolution is that in this one, the social aspects are more important than the purely technological ones based on digitalization. The focus of Industry 5.0 is to take actions for the benefit of humanity (Xu *et al.*, 2021).

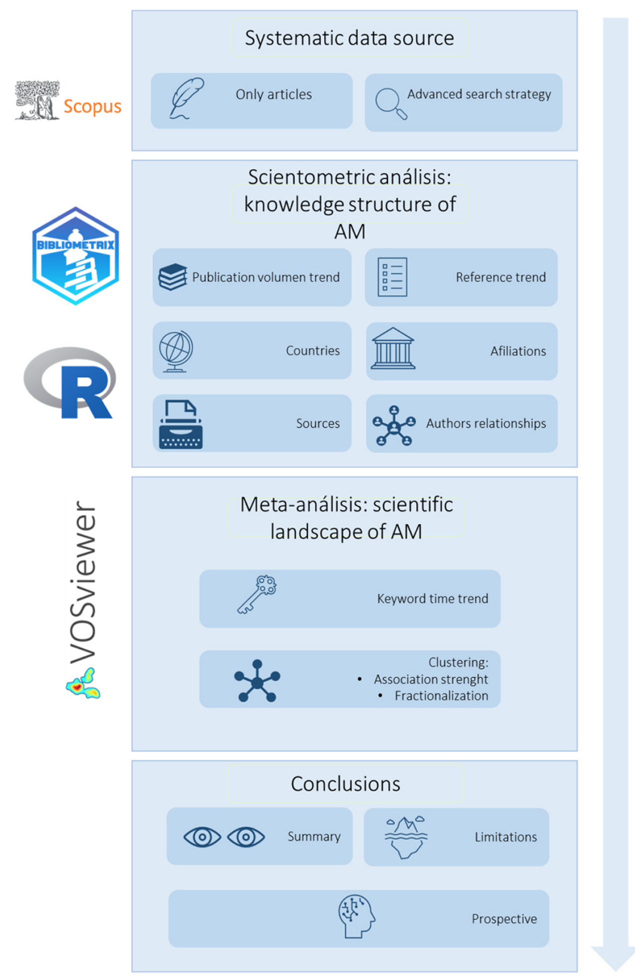
Due to the multidisciplinary and cross-disciplinary activities that involve the AM, even more so in this time of the 4th and 5th industrial revolutions, it is extremely important to know the direction in which new developments are taking place. Furthermore, currently, AM cannot be seen as an independent process (Lee *et al.*, 2017) and takes part as a pillar in Industry 4.0 (Parvanda and Kala, 2023) and Industry 5.0 (Zhou *et al.*, 2020). So, in this article, the main contribution is related to the novel use of large bibliographic data sets to implement scientometrics and meta-analysis since this type of advanced analysis helps to identify gaps in research and characteristics of existing experiences and potential applications (Dorado-Vicente *et al.*, 2022) and also helps to evaluate the quantity and quality of the research development in the technological context of the AM. This subject is especially important in the current context of industrial transformation, where different trends should be quickly identified to generate prospective takeaways in research planning and not be left behind.

2. Methodology

The methodology applied (Figure 1) to this work is based on bibliometric and analytical tools applied to scientometrics. The aim is to extract information from the bibliographic data and metadata to draw conclusions and establish a perspective on the evolution of AM in the context of Industry 4.0.

For this work, a large bibliographic data set will be systematically extracted from the well-known scientific database Scopus, which spans 330 disciplines, ensuring researchers have the assurance they are accessing all the critical information necessary for research. Scopus covers 7,000 publishers' content and undergoes thorough evaluation and selection by an independent Content Selection and Advisory Board (CSAB) (Scopus, 2024), ensures that only research of high quality and relevance is included, which is crucial for conducting a rigorous bibliometric analysis. Considering the specific research field, Scopus is a database that covers a large number of science and engineering articles (Mongeon and Paul-Hus, 2016), so it is considered a valid database for this research. Finally, the database's operable interface and the ability to export data easily for further meta-analysis using an open programming language

Figure 1 Graphical summary of the methodology applied for this work and the software used



Source: Figure by authors

such as R. For these reasons, Scopus was chosen to generate the data sets. It is noteworthy that when using a database (although very complete and with great acceptance among the scientific community), the authors of this work are working on a sample of papers, and this can always involve a bias. However, the large number of sources collected by Scopus and the quality indicators required to be part of its database make it very unlikely that the results would be significantly different using other databases that apply the same quality standards.

For the first time, different filters and logical exclusion criteria will be applied to efficiently find those works directly related to the AM research field. The aim is to try to have a manageable data set of the most representative works in AM.

2.1 Scientometric analysis

Firstly, a scientometric analysis will be implemented to observe the knowledge structure of the AM field. For this purpose, the publication volume trend in AM will be evaluated. Also, the reference trend is needed to know the impact and development of either the source or paper. The sources will be analysed in terms of impact and also (due to the high multidisciplinary nature of AM) in terms of scope to determine the relationship of AM to different scientific fields: manufacturing and materials. Additionally, the percentage of open-access publications will be obtained and compared with respect to the percentage of all the publications databased in Scopus. The affiliations and their countries will also be considered to determine the geographical development of the field and to know the framework of the main relationships.

To meet this objective, a descriptive analysis of the data will be applied for the creation of attributes that allow for its normalization and the visualization of its temporal evolution in terms of volume, as well as the measurement of the impact of the sources. Different functions and parameters commonly used in scientometrics will be used: the well-known Bradford law postulates that most articles on a specialized subject may be published by a few journals specially dedicated to that subject (Bradford, 1985). To know the impact in terms of references foreach source, the H index (Hirsch, 2005) will be applied to the journals. The H index represents the quantity of x papers, published in a journal, that have received at least x citations. However, other indexes will be used to enhance the analysis. In this way, the G index (Egghe, 2006) will be applied. This index shows the top g articles received (together) at least g^2 citations. Finally, the M index will also be obtained. This last index shows the H-index per year since the first publication. The researchers productivity will be evaluated using the well-known Lotka's law (Lotka, 1926) applying the inverse square law (60% of authors produce only one paper, while the percentage of the following is calculated as 1/n^2, being *n* the portion of articles written). The evaluation of the relationships between the researcher's affiliations will be implemented using a collaboration Worldmap where each connection is drawn.

Firstly, different filters and logical exclusion criteria will be applied to efficiently find those works directly related to the AM research field. The aim is to try to have a manageable data set of the most representative works in AM.

Additionally, the papers with the highest number of citations will be searched for, and the timespan for this analysis will be established in eight years since this period corresponds to the period of greatest development of AM and Industry 5.0. Based on this data set, two analyses will be addressed: a quantitative analysis based on the citation number of each paper and additional statistical information and a qualitative analysis based on the content of the paper from a classification according to its typology (as a review paper (technical), a review paper (trends/market), and a research paper). In this way, by observing the papers with the greatest impact and comparing them with the results extracted from the total set of sources analysed, it will be possible to get an idea of the trends in research in AM.

2.2 Meta-analysis

Once the scientometric analysis has been implemented, keywords will be considered to evaluate the time trend to discover the evolution of the topic trends within AM. Subsequently, clustering strategies will be applied to generate a co-currency network matrix. This will enable the generation of network mapping but previously, to avoid word redundancy and analyse the relationships between fields, the keywords set for the search will be discriminated for clustering. Thus, different clustering parameters will be established (iteration number, initial step size, step size reduction and step size convergence) to generate a coherent number of clusters with enough strength between links and keyword density.

Table 1 Advanced search criteria used to extract the data set 1

Criteria type	Keywords
Keywords ("or")	(LIMIT-TO (EXACTKEYWORD, "Additive Manufacturing") OR LIMIT-TO (EXACTKEYWORD, "3D Printers") OR LIMIT-TO (EXACTKEYWORD, "Selective Laser Melting") OR LIMIT-TO (EXACTKEYWORD, "3D Printing") OR LIMIT-TO (EXACTKEYWORD, "3-D Printing") OR LIMIT-TO (EXACTKEYWORD, "Additive Manufacturing Process") OR LIMIT-TO (EXACTKEYWORD, "Additive Manufacturing Technology") OR LIMIT-TO (EXACTKEYWORD, "Fused Deposition Modeling") OR LIMIT-TO (EXACTKEYWORD, "3D-printing") OR LIMIT-TO (EXACTKEYWORD, "Three Dimensional Printing") OR LIMIT-TO (EXACTKEYWORD, "Selective Laser Melting (SLM)") OR LIMIT-TO (EXACTKEYWORD, "Laser Additive Manufacturing") OR LIMIT-TO (EXACTKEYWORD, "Selective laser sintering") OR LIMIT-TO (EXACTKEYWORD, "Laminated Object Manufacturing") OR LIMIT-TO (EXACTKEYWORD, "Laser powder bed fusion"))
Year	Data set: 2015–2023 (eight years)
Document type	Only article (restrictive) with the final version published
Total references	Data set 1: 19,666 (date: 04/07/2023)
Filtering	Non-applied

Source: Table by authors

Table 2 Advanced search criteria used to extract the data set 2

Criteria type	Keywords, title and abstract
Keywords ("or")	(TITLE-ABS-KEY ("additive manufacturing") OR TITLE-ABS-KEY ("3d printing") OR TITLE-ABS-KEY ("3-d printing") OR TITLE-ABS-KEY ("3d printers") OR TITLE-AS-KEY ("3-d printers")) AND PUBYEAR > 2016 AND PUBYEAR < 2025
Year	Data set: 2015–2023 (eight years)
Document type	All
Total references	Data set 1: 100 (date: 25/09/2023)
Filter	More referenced papers

Source: Table by authors

In this way, interrelationships between keywords (in addition to those related to additive manufacturing) can be visualized and different clusters can be generated to evaluate the taxonomy of the AM research field.

Using Vosviewer (Leiden University, 2022), two clustering strategies will be used to evaluate the clusters from different perspectives. On the one hand, the Association Strengths Method was used to normalize the strength of the links between keywords. On the other hand, the Fractionalization Method was used for the same goal. The two methods differ in the equation for calculating the scientometrics measures, as stated in detail in Van Eck and Waltman (2009).

Follow these strategies, different clusters will be generated based on the relationships between keywords. These will be qualitatively evaluated in terms of the strength of the link and the intensity of the connection with other clusters.

To perform the analysis, two tools will be used: frome one perpesctive, the R library Bibliometrix (Aria and Cuccurullo, 2017) will be used to generate the scientometric analysis and, consequently, evaluate the knowledge structure. From another perspective, to complete the meta-analysis through the generation of co-occurrence networks, Vosviewer (Leiden University, 2022) will be used.

Table 3 Summary of the results obtained in each data set

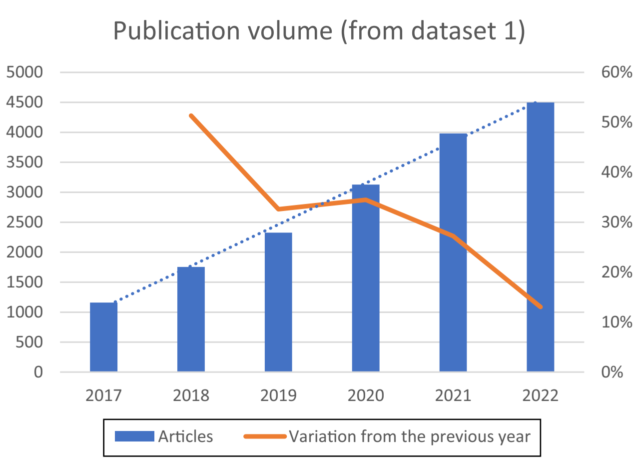
Data set 1	
Timespan	2017–2023
Sources	1,774
Documents N°	19,414
Annual growth rate	14.18
Authors	41,582
Mean co-authors per work	5.11
Authors single-authored	279
International co-authorship	23.77%
References	630,905
Document Av. Age	2.41
Av. citations per docs	18.71
Data set 2	
Timespan	2017–2021
Sources	52
Documents N°	100
Annual growth rate	−50.75%
Authors	516
Mean co-authors per work	5.63
Authors single-authored	2%
International co-authorship	44%
References	11,489
Document Av. Age	4.85
Av. citations per docs	716.2

Source: Table by authors

3. Results

The well-known scientific database Scopus was used to extract two large data sets of publications, which contain all the information that allows obtaining the data for each document found. The search criteria used are those indicated in Table 1. To avoid an excessively large amount of data, only articles in scientific journals were considered, discarding publications in other media. Different keywords that can be used similarly were used as criteria for "or". The first data set contained 19,666 scientific papers, while the second data set contained 9,016. Additionally, a second data set (data set 1) was extracted. This is only applied to evaluate the 100 most cited articles on AM (Table 2). To collect the data, it has been taken into account to approximately coincide with the development period of the current Industry 5.0 paradigm: the last 7–10 years (Demir *et al.*, 2019; Longo *et al.*, 2020; Nahavandi, 2019).

Figure 2 Evolution of the publication volume on AM during the evaluated period, including the percentage change from the previous year



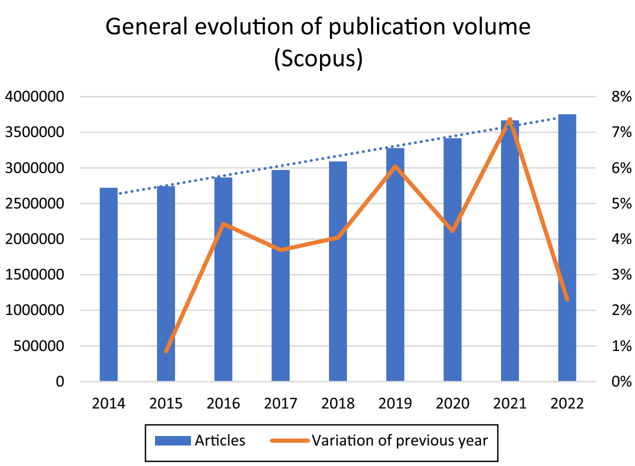
Notes: This has been calculated using the dataset 1. Please note that to evaluate the real trend based on complete years, the articles published during 2023 are not shown in this plot
Source: Figure by authors

The description of data sets 1 and 2 is shown in Table 3. From this first analysis, differences can be detected in the average number of authors and in the percentage of internationalization. The most cited articles (data set 2) have been signed by a greater number of authors and with greater international collaboration. The most cited articles belong to 52 sources, while the data set encompassing all papers records articles from 1774 sources.

3.1 Results of the bibliometric analysis

Once an overview of the data sets has been implemented, an analysis of the time trend for the number of articles (volume) is performed based on data set 1. The percentage variation for each year was calculated with respect to the previous year (Figure 2). In this analysis, it can be seen how the volume of articles is increasing. The growth rate (288%) is much higher than that shown by the total number of articles registered in Scopus (37%) for the same period (Figure 3). However, although the trend is clearly upward, in relative terms, it is slowing down.

Figure 3 Evolution of the publication in Scopus evaluated period including the percentage change from the previous year



Notes: Please note that to evaluate the real trend based on complete years, the articles published during 2023 have not shown in this plot
Source: Figure by authors

To know the intellectual structure (and based on data set 1), an analysis of the sources was carried out based on the number of references and temporal evolution. Since the Open-Access format provides wider dissemination and visibility and enhances research collaboration, the percentage of publications published in Open Access was 51% (for data set 1) and 50% for the last two years. This shows that the number of publications in open access is not significantly growing. However, this percentage is higher than those provided by Scopus for all scientific articles (in journals) in English (51% of articles in open access for the last 8 years and 54% for the last two years).

Only scientific journal articles were considered after applying a filter, the Bradford Law was employed to determine the most influential journals. Table 4 and Figure 4 display the journals classified as core sources in Zone 1. As the reader can see, and considering the first five positions, the journal that obtains the most references (Additive Manufacturing) is a journal that specializes specifically in AM. The second one is a journal specializing in materials science and engineering, while the third is a journal specializing in manufacturing technology (not just AM). It is interesting that within the top journals, there is one specialized in fast prototyping (Rapid Prototyping Journal).

The evolution in the volume of publications of the main journals was evaluated individually Figure 5) and compared to the rest of the journals. The journal with the highest publication volume (Additive Manufacturing) is also the one that has developed the highest growth rate during this period. The second (Materials) and third journals (Materials and International Journal of Advanced Manufacturing Technology, respectively) have shown a very similar evolution.

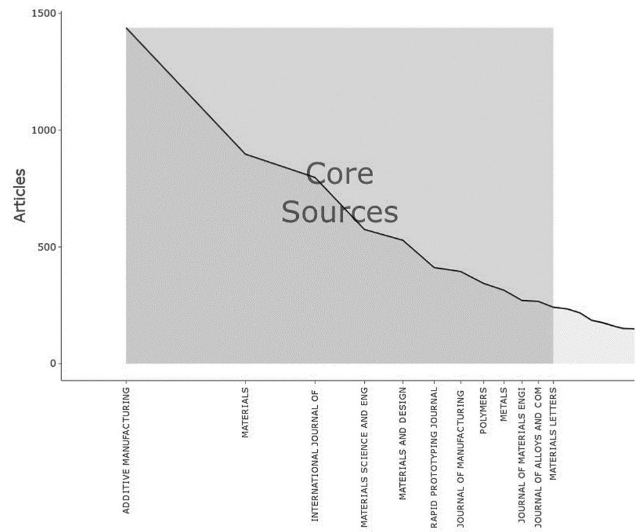
To implement a deeper analysis, the sources were grouped into two categories: one related to "manufacturing processes" and the other associated with "materials". The results obtained were compared to detect the evolution of AM within each topic. The evolution was similar, being slightly more intense for the sources related to manufacturing processes (Figure 6).

Table 4 Most relevant sources based on references (2013–2023) of the publications in data set 1

Source	Rank	Frequency	Cumulative frequency
Additive Manufacturing	1	1,438	1,438
Materials	2	897	2,335
International Journal of Advanced Manufacturing Technology	3	797	3,132
Materials Science and Engineering: A	4	574	3,706
Materials and Design	5	528	4,234
Rapid Prototyping Journal	6	411	4,645
Journal of Manufacturing Processes	7	394	5,039
Polymers	8	343	5,382
Metals	9	314	5696
Journal of Materials Engineering and Performance	10	270	5,966
Journal of Alloys and Compounds	11	266	6,232
Materials letters	12	241	6,473

Notes: All the sources are located in Zone 1 following Bradford Law (applied to data set 1). The remaining 1,960 sources obtained 12,398 references. Please note that this index is calculated from the extracted publication's data and is not the same as *H and G journal* indexes
Source: Table by authors

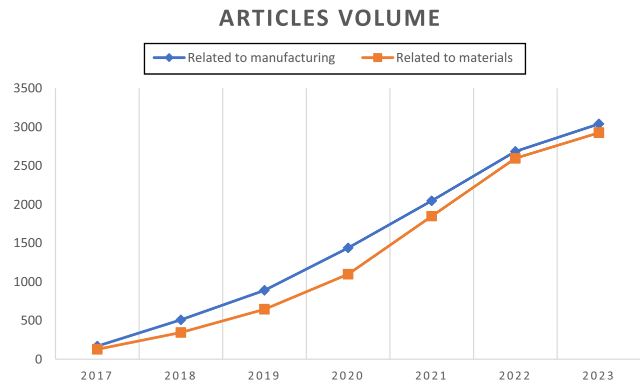
Figure 4 Brandford law diagram for sources



Source: Figure by authors

When the five more important journals have been selected for the four more important countries in terms of volume to compare the weight in each territory (European Union (EU), China, USA (USA), and the UK (UK)). In this way, more representative journals can be evaluated in a geographical context. Table 5 reveals that the establishment of the more representative journals is not uniform across all countries. While in the EU, the first journal was related to materials science and engineering (with a very wide scope), for the rest, the first journal was related to Additive Manufacturing (with a highly focused AM scope). In China, a journal very related to alloys and metallurgy raised position number 3, while this journal was not in the TOP-5 of the rest of the of the countries.

Figure 6 Sources related to manufacturing vs sources related to materials



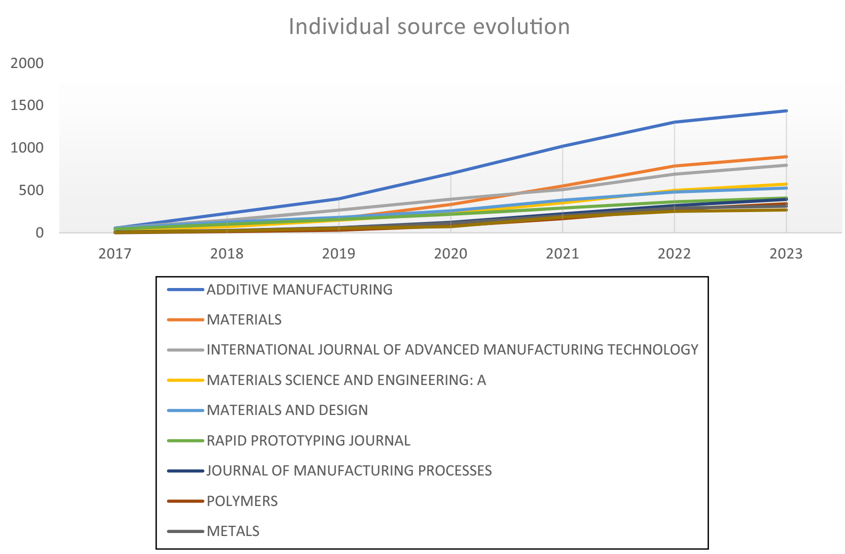
Source: Figure by authors

To evaluate the distribution of the publications, a Pareto analysis of the articles from each country was conducted (Table 6). The Pareto principle applied to publications would be stated in this way: 20% of the sources contain around 80% of the articles. This principle is the same in the case of China and very similar in the EU and USA. In China (and also in the EU and USA), the articles are concentrated on fewer sources, in the UK the opposite is true.

The Pareto principle is considered for each one of the countries:

To evaluate the number of authors publishing a specific number of articles, Lotka's law was applied (Figure 7). It implies that the Betta coefficient is equal to 2 (the theoretical result from the inverse square law). In this case, as the reader can see in Figure 4, there is a deviation in the real curve with respect to the theoretical curve: more than 60% of authors have published only one paper and the number of authors who

Figure 5 Individual time evolution of each journal



Source: Figure by authors

Table 5 Most relevant sources by country

EU		
Materials	526	7.50%
Additive Manufacturing	408	5.81%
International Journal of Advanced Manufacturing Technology	274	3.90%
Polymers	210	2.99%
Materials and Design	167	2.38%
	1,585	22.58%
USA		
Additive Manufacturing	605	12.24%
International Journal of Advanced Manufacturing Technology	161	3.26%
Materials Science and Engineering: A	143	2.89%
Materials and Design	130	2.63%
Journal of Manufacturing Processes	118	2.39%
	1,157	23.41%
China		
Additive Manufacturing	255	6.47%
Materials Science and Engineering: A	236	5.99%
Journal of Alloys and Compounds	150	3.80%
Materials and Design	133	3.37%
Materials	132	3.35%
	906	22.98%
UK		
Additive Manufacturing	146	9.16%
Materials and Design	68	4.27%
International Journal of Advanced Manufacturing Technology	58	3.64%
Materials	40	2.51%
Materials Science and Engineering: A	36	2.26%
	348	21.83%

Source: Table by authors

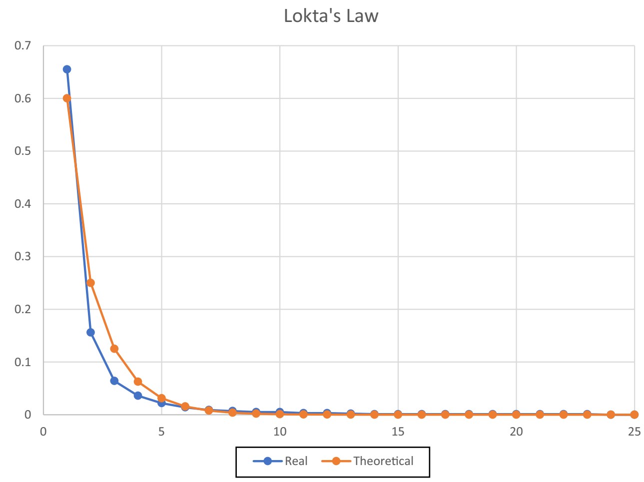
publish a low number of articles is higher than the expected value.

The H and G indexes were evaluated, considering the publications of each journal included in data set 1 (Figure. 8), to provide a comparison based on the same objective indexes. It is to be expected that the G index will be higher than the H index since the G Index allows citations from articles with a higher number of citations to be used to reinforce articles with a lower number of citations. Additive Manufacturing is the journal with a higher H. However, Materials and Design (that is, number five in terms of volume as stated in Table 4) is the second journal with a higher H and the TOP1 if the G-index is considered.

Although most information on sources is obtained by considering the sources, important qualitative information can also be obtained if the most cited works are studied individually (Rodríguez-Martín *et al.*, 2023). In this way, the most cited articles were extracted from data set 2 (Table 2). These are presented in Table 7. As anticipated in a rapidly evolving field, most cited works are reviews. Metal additive manufacturing was the subject of the most cited research articles.

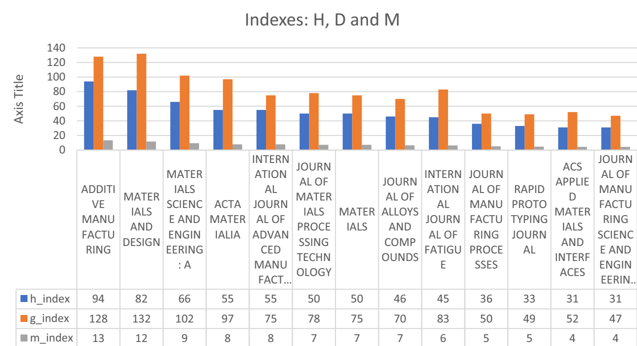
The main affiliations were studied to evaluate productivity (Table 8). The 10 top paper production institutions raised 28.8%

Figure 7 Proportion of authors who have written a given number of publications (from data set 1)



Source: Figure by authors

Figure 8 H and G index based on the source analysis of data set 1



Notes: Please note that these indexes are calculated from the extracted publication's data, and these are not the same as the indexes H and G for the Journal
Source: Figure by authors

Table 6 Pareto principle from the most relevant sources by country

Country	Total articles	Sources	Sources within 20%	Articles within the 20% of sources	
EU	7,018	1,015	203	5,526	78.74%
The USA	4,943	752	151	3,867	78.23%
China	3,943	539	108	3,166	80.29%
The UK	1,594	430	86	1,106	69.39%

Source: Table by authors

Table 7 More relevant works based on references volume

Type**	Tittle	T.C.*	T.C.p.y.	Norm. T.C.
W	Additive manufacturing (3D printing): a review of materials, methods, applications and challenges (Ngo *et al.*, 2018)	4,194	699.00	4.87
W	Additive manufacturing of metallic components – Process, structure and properties (DebRoy *et al.*, 2018)	4,102	683.67	4.76
W	3D printing of polymer matrix composites: a review and prospective (Wang *et al.*, 2017)	2,150	307.14	3.02
R	Polymers for 3D printing and customized additive manufacturing (Ligon *et al.*, 2017)	2,139	305.57	3.01
R	3D printing of high-strength aluminum alloys (Martin *et al.*, 2017)	1,677	239.57	2.36
R	Additively manufactured with high strength and ductility (Wang *et al.*, 2018)	1,319	219.83	1.53
W	Additive manufacturing of Ti6Al4V (Liu and Shin, 2019)	1,259	251.80	2.04
R	Printing ferromagnetic domains for untethered fast (Kim *et al.*, 2018)	1,179	196.50	1.37
W	3D printing of ceramic: a review (Chen *et al.*, 2019)	1,109	221.80	1.80
W-T	Additive manufacturing: scientific and technological challenges, market uptake and opportunities (Tofail *et al.*, 2018)	1,088	181.33	1.26
W	Stretchable and soft electronics using liquid metals (Dickey, 2017)	1,041	148.71	1.46
W-T	Literature review of Industry 4.0 and related technologies (Oztemel and Gursev, 2020)	942	235.50	1.63
W	Fundamentals and applications of 3D printing for novel materials (Lee *et al.*, 2017)	865	123.57	1.22
R	Additive manufacturing of PLA structures using fused deposition modelling: effect of process parameters on mechanical properties and their optimal selection (Chacón *et al.*, 2017)	859	122.71	1.21
W	Mechanical characterization of 3D-printed polymers (Dizon *et al.*, 2018)	856	142.67	0.99
W-T	The rise of 3-D printing: the advantages of additive manufacturing over traditional manufacturing (Attaran, 2017)	854	122.00	1.20
W-T	The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics (Ivanov *et al.*, 2019)	832	166.40	1.35
W	Scaffolds for bone tissue engineering: state of the art and new perspectives (Roseti *et al.*, 2017)	828	118.29	1.16
W	3D bioactive composite scaffolds for bone tissue engineering (Turnbull *et al.*, 2018)	789	131.50	0.92
W	Anisotropy and heterogeneity of microstructure and mechanical properties in metal additive manufacturing: a critical review (Kok *et al.*, 2018)	780	130.00	0.91
W	3D printing of aluminium alloys: additive manufacturing of aluminium alloys using selective laser melting (Aboulkhair *et al.*, 2019)	779	155.80	1.26
W	A review on additive manufacturing of polymer-fiber composites (Parandoush and Lin, 2017)	756	108.00	1.06
W	3D printing using concrete extrusion: a roadmap for research (Buswell *et al.*, 2018)	750	125.00	0.87
W	Review on titanium and titanium-based alloys as biomaterials for orthopedic applications (Kaur and Singh, 2019)	740	148.00	1.20
W	An overview of 3D printing technology: technological, materials, and applications (Shahrudin *et al.*, 2019)	697	139.40	1.13

Notes: This categorization has been based on the authors' criteria (not from metadata); **T.C.is* "total citations". *T.C.* p *Y. is* "total citation per year", *Norm. T.C. is* "normalized T.C". ***The type of paper has been determined by the authors*; R is used for review paper (technical), R-T for review paper (trends/market) and W for research paper
Source: Table by authors

Table 8 Affiliations with a higher production

Affiliation	Country	Articles	Proportion (%)
Huazhong University of Science and Technology	China	939	4.77
Northwestern Polytechnical University	China	921	4.68
Dalian University of Technology	China	548	2.79
University of Nottingham	The UK	492	2.50
Politecnico di Milano	Italy	482	2.45
Nanjing University of Aeronautics and Astronautics	China	474	2.41
Tsinghua University	China	462	2.35
Singapore	Singapore	457	2.32
Beihang University	China	450	2.29
Shanghai Jiao Tong University	China	442	2.25
Total		5,667	*28.82*

Source: Table by authors

of the total articles in the data set. It implies that there are a lot of sources (mainly due to the high multidisciplinary and cross-disciplinary nature of the AM topic). The affiliation with China is the most frequent. However, the country contributing the most scientific articles to the topic is the European Union, followed by the USA, with China in third place. This could indicate a significant concentration of publications in China, centered around a smaller number of individuals with Chinese affiliations.

The links between authors of affiliations from different countries were computed to analyse the geographical interrelationships.

A collaboration world map was drawn to evaluate the relationship between the authors and institutions. China, the USA, the European Union, Japan, Australia, and the UK are the countries with a higher number of connections. For the first time, global interrelationships are considered (Figure 9).

With the aim of evaluating in detail and comparing the volume and parts of the interrelationships, a segmentation by countries of the relationships was made. Collaboration between the European Union and the US is very frequent, and collaboration between China and the US is less frequent (Figure 10).

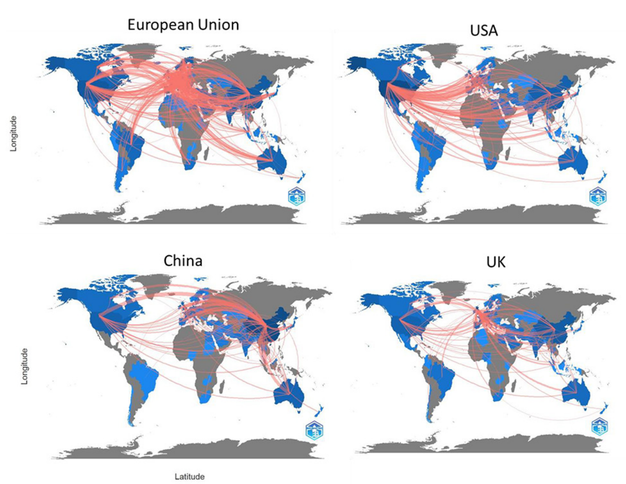
3.2 Results of the meta-analysis

Once the publication volume, sources, and social structure had been evaluated in the context of Once the publication volume, sources, and social structure had been evaluated in the context of the bibliometric analysis, a based-on-keywords meta-analysis was implemented. For the first time, a keyword trend table was calculated based on the repetition of the keyword by year (Table 9). In this case, keyword plus was used as the as the unit of analysis,

Figure 9 Global distribution of the relationships between researchers of different countries

Source: Figure by authors

Figure 10 Relationships of the authors of the countries with a higher research production



Source: Figure by authors

Table 9 Keyword plus analysis considering word minimum frequency of 5 and 5 main words per year

Keyword	Freq	Year Q1	Year Q2	Year Q3
2017				
Manufacture	331	2017	2017	2018
Mesenchymal stromal cells	13	2017	2017	2022
Niobium	13	2017	2017	2018
Fighter aircraft	11	2017	2017	2018
Industrial ecology	10	2017	2017	2017
2018				
Characterization	30	2018	2018	2022
Biomaterials	20	2018	2018	2019
Stress, mechanical	14	2018	2018	2019
Three-dimensional imaging	14	2018	2018	2019
Assembly	13	2018	2018	2022
2019				
Mechanical properties	262	2018	2019	2020
Priority journal	99	2018	2019	2020
Biomaterial	90	2018	2019	2021
Aluminum	87	2017	2019	2021
Ceramic materials	71	2018	2019	2020
2020				
Selective laser melting	895	2019	2020	2022
Melting	531	2018	2020	2021
Porosity	491	2019	2020	2022
Sintering	478	2019	2020	2022
Computer aided design	280	2019	2020	2022
2021				
Additives	3,183	2020	2021	2022
Aluminum alloys	647	2019	2021	2022
Microstructure	585	2019	2021	2022
Deposition	564	2019	2021	2022
Titanium alloys	552	2019	2021	2022
2022				
Laser powders	462	2021	2022	2023
Laser powder bed fusion	201	2022	2022	2023
Wire	188	2020	2022	2023
Energy depositions	138	2021	2022	2023
Photopolymerization	35	2022	2023	2023
2023				
Material extrusion	57	2022	2023	2023
Ductile fracture	45	2022	2023	2023
Photopolymerization	35	2022	2023	2023
Machine-learning	31	2022	2023	2023
Image correlation	28	2022	2023	2023

Source: Table by authors

considering the minimum frequency of 1 and 10 main words per year. This analysis shows that keywords related to the additive manufacturing of metals represent the latest trend. The topics have evolved from the characterization of materials to the 3D printing of metals. This is a coherent cycle of evolution.

Finally, two networks based on co-occurrence keywords were generated using data set 1. Previously, authors removed keywords that were associated with those that had been used as search criteria. Therefore, it is feasible to eliminate unnecessary connections and focus solely on the remaining keywords (excluding those specified in Table 1 as search criteria). To simplify the network and avoid searching for irrelevant connections, the authors set a criterion that only keywords repeated at least 20 times would be reproduced. The clustering method employed was normalization based on association strength. Additionally, to enhance the analysis, a clustering method utilizing fractionalization was also implemented. The arrangement and groupings may vary when these two distinct approaches are implemented. In both instances, a total of 10 iterations were utilized, resulting in the merging of smaller clusters.

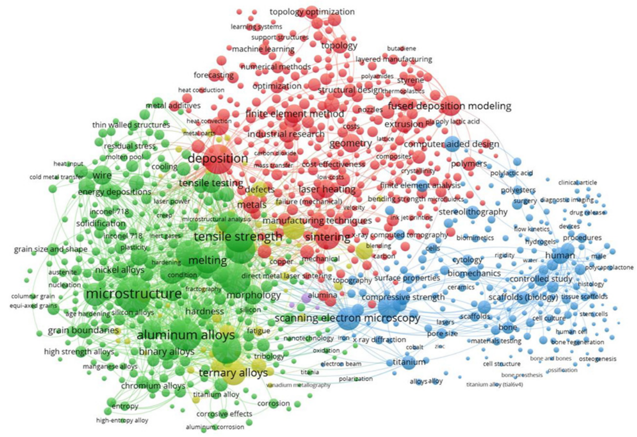
The clusters obtained are shown in Table 10 and they can be compared in terms of the strength of the link and connection with other clusters. Although the boundaries are not totally defined, it is possible to differentiate different themes from the clustering process. The number of clusters was generated based on the association strength.

As the reader can see in Figure 11, the main related keywords are microstructure and mechanical properties. There is an important relationship between them, so they are simultaneously referenced in lots of works. Other keywords remain important in the network, such as those related to filament manufacturing and topological optimization.

When a method of clustering based on fractionalization was used, four important clusters were generated (Table 11, Figure 12). Cluster 1 and cluster 3 of the last maps are conserved with slight changes (now cluster 1 and cluster 2 in Figure 12). However, the main novelty lies in the division of cluster 2 (Figure 11) into two clusters, 3 and 4. So, using this strategy, cluster 3 specifically related to Industry 4.0 and design was established.

The relationships among the main additive technologies were analysed individually using the strength of the link (Figure 13). The technique with the greatest impact is Selective Laser Melting (SLM). Selective Laser Melting (SLM) closely aligns with keywords that pertain to the mechanical properties of metals and alloys, along with laser heating sources. FDM technology shares a less intense relationship with keywords related to the mechanical and thermal properties of materials. At the same time, it is related to concepts typical of the addition of plastics to polymers. Several keywords related to the microstructure of materials are also associated with laser sintering. Finally, the scope of stereolithography is almost residual, perhaps because it is the oldest and most consolidated technique (outside of the focus of research work).

Figure 11 Keyword plus analysis considering word minimum frequency of 5 and 5 main words per year



Notes: The circle size indicates the frequency of the keyword, and the length of the lines shows how long the keyword has been contemplated
Source: Figure by authors

4. Discussion

The relationship and development of the AM as a pillar of Industry 4.0 have become clear for different reasons:

- due to the topicality of the subject matter and the incipient development;
- due to the grouping of publications around sources of technological scope related to manufacturing methods;
- due to the recent creation and development of journals specialized in AM;

Table 10 Qualitative analysis of clusters generated from data set 1 using a clustering association strength clustering strategy

Cluster	Description		Keyword density	Strength of the link	Connection with other clusters
Cluster 1 (green)	"Microstructure" is highly related to alloys and metallics materials, alloys and heat treatments. Keywords are very repetitive and concentrated	343	High	High	High
Cluster 2 (red)	Several keywords with lower repetition rates than Cluster 1. Directly related to fusion deposition model technology, optimization and 4.0 technologies such as machine learning or simulation	329	Medium	Medium	High
Cluster 3 (blue)	Many keywords have weak links but are very related to biomechanics, human and medical uses of AM in general. One part of the cluster is more transversal and more related to the other two clusters (scanning electron microscopy, stereolithography, etc.). These keywords could also be located in Clusters 1 or 2, but the other part of the cluster is more isolated and it is really related to medical uses of AM.	249	Medium	Low	Medium

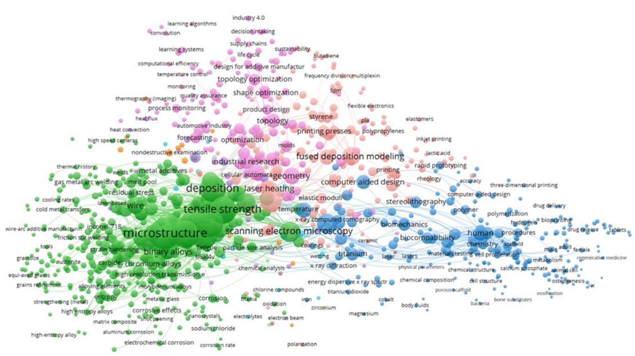
Note: In total, 984 keywords were considered
Source: Table by authors

Table 11 Qualitative analysis of clusters generated from data set 1 using a clustering fractionalization clustering strategy

Cluster	Description		Keyword density	Strength of the link	Connection with other clusters
Cluster 1 (green)	Fitted to Cluster 1 of the last method. However, in this case, some keywords of Cluster 2 of the last method are also contemplated (e.g. deposition, tensile testing, etc.)	389	High	High	High
Cluster 2 (blue)	This cluster is very similar to Cluster 3 calculated using the last method	237	Medium	Medium	Medium
Cluster 3 (pink)	This cluster includes keywords of Cluster 2 of the last method. Mainly those related to Industry 4.0, quality, optimization and design	163	Medium	Medium	Medium
Cluster 4 (orange)	This cluster includes keywords of Cluster 2 of the last method. Mainly those related to the FDM technology	127	Medium	Low	Medium

Note: In total, 984 keywords were considered
Source: Table by authors

Figure 12 Network map for data set 1 by association strength that shows the keywords of the articles linked with the keyword Additive Manufacturing (and similar terms) and the relationship between them



Source: Figure by authors

- due to the worldwide incidence and the high number of international research relationships found, and
- finally, due to the relationships found in the meta-analysis between AM and other technologies inherent to Industry 4.0 such as AI, IoT, etc.

This has been established in this way by different authors (e.g. Xu *et al.*, 2021; Khorasani *et al.*, 2022; Oztemel and Gursev, 2020) and their approach is consistent with that investigated in this work.

Additive Manufacturing was the journal with the highest impact based on H-Index. Therefore, a journal specifically created for the subject is the most cited. This shows the disruptive component of the subject and the rapid and recent development of scientific literature in this field (existing journals have not been enough but have led to the transdisciplinary creation of new journals). However, an analysis of the G-index revealed a higher G-index for the journal Materials and Design. Considering that the G-index is less restrictive than the H-index, this may show that this journal publishes more research that has reached a medium number of citations (counted for the G-index but not for the H-index).

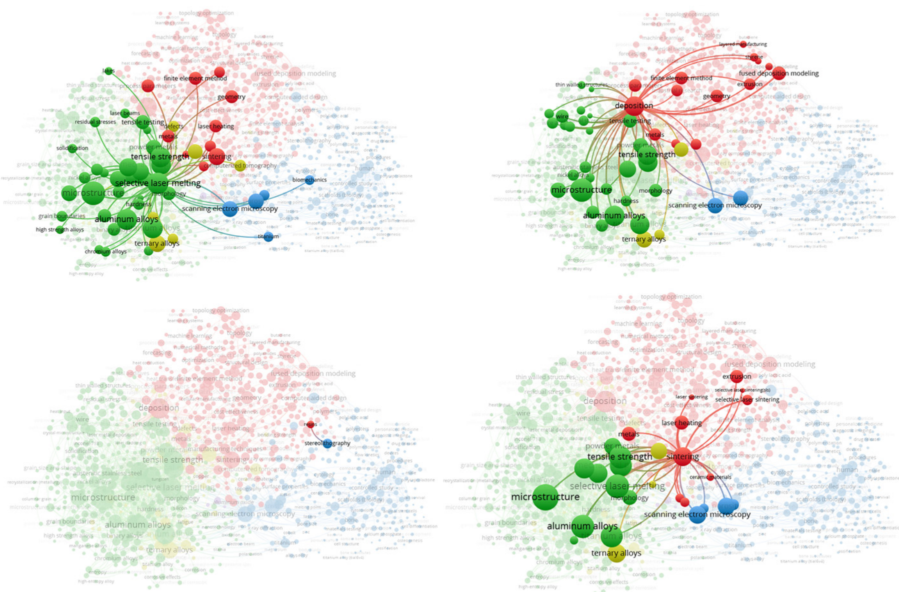
The application of Lokta's Law reveals a greater number of authors who have only published a single AM-related paper. The novelty of certain additive technologies and the rapid development in these years justify this.

The evolution of the keywords shows that additive manufacturing of metals—specifically, laser powders, aluminum alloys, and titanium alloys—is gaining importance. It is compatible with the publication of several review works about this issue (e.g. there exist different current review works that address different aspects of AM for metals) (Aboulkhair *et al.*, 2019; Carolo and Cooper O., 2022; Gong *et al.*, 2023; Kaur and Singh, 2019; Khorasani *et al.*, 2023a, 2023b, 2023c; Orzolek *et al.*, 2022; Slavkovic *et al.*, 2023; Springer *et al.*, 2023; Talignani *et al.*, 2022; Volpato *et al.*, 2022).

The meta-analysis reveals three main clusters that align with subtopics within the field of additive manufacturing. The most representative cluster was found to be related to the AM of metals and the characterization of metallic materials. This is compatible with the results of the preliminary analysis addressed in (Rodríguez-Martín *et al.*, 2023). The second subtopic concerns to FDM technology, filament manufacturing, simulation, and Industry 4.0. This is compatible with AM, which has already been referred to in 2015 as one of a series of disruptive technologies, and AM is changing the way we design products and set up new businesses (Gibson *et al.*, 2015).

Depending on the clustering method used, this subtopic can be further divided into two: one related to FDM technology, thermoplastic extrusion, and composite materials, and another subtopic related to 4.0 / 5.0 technologies (simulation, optimization, computer design, machine learning, learning systems, forecasting, etc.) and other concepts related to quality, digitalization and new approaches in industry (thermography, supply chain, process monitoring, quality, sustainability, etc.). It is important to note that this subtopic does not appear in the other 20 referenced papers, primarily because of its novelty and recent publication date, which has prevented it from accumulating a significant number of citations. However, the importance of this topic is very intense since AM must be considered within the 4.0 industry and take advantage of artificial intelligence methods for its own manufacturing system (Qin *et al.*, 2022) and also for testing and NDT methods for quality inspection of manufactured-by-AM parts (Rodríguez-Martín *et al.*, 2022). This topic is currently developing and due to its

Figure 13 Network map for data set 1 by association strength that shows the keywords of the articles linked with the main keyword related to main AM technologies: powder bed fusion (up-left and down-right), material extrusion (up-right) and vat photopolymerization (down-left)



Source: Figure by authors

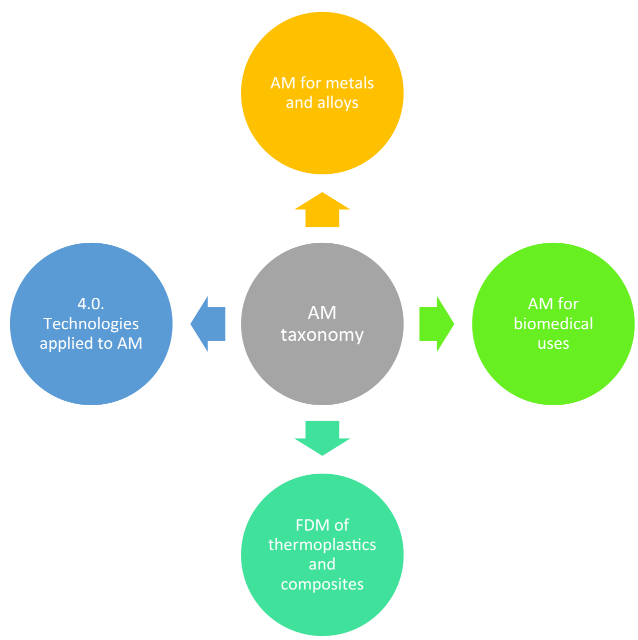
novelty, it is now stronger than in previous meta-analyses on AM (Kabir *et al.*, 2020). The third subtopic is related to the medical and health uses of AM (previously mentioned), and it is compatible with other meta-analyses made for the last period (Kabir *et al.*, 2020). It is pertinent to recognize that the social and sustainability applications of additive manufacturing (AM) align more closely with the concept of Industry 5.0. This is because AM includes three interconnected essential principles: human-centricity, sustainability, and resilience. Furthermore, AM has been developed over the past seven years (Xu *et al.*, 2021).

Summarizing, based on meta-analyisis, it could be said that the taxonomy of research developments in AM can be summarized in the following categories (Figure 14).

Perhaps because of the novelty of the Industry 5.0 approach, there has been less exploration of the relationship between AM and Industry 5.0. However, insofar as Industry 5.0 puts the focus more on the social domain in how technologies help humanity (Breque *et al.*, 2021), it is clear that the relationships found between AM and different health and social domains (even with the exact keyword "human") could make this technology a dynamic element of Industry 5.0 with a very large development potential in the future (based on the trend results provided in this work).

Therefore, it is foreseeable that AM will play a relevant role in the two industrial paradigms with which humanity currently coexists (Industry 4.0 and 5.0), without excluding the risks that may affect the normal development of this technology, which has been evaluated for some specific sector. For example, for the AM applied to construction, the identified risks are based on materials, equipment, environment, management, stakeholders, regulatory and economic factors, and, also, cybersecurity (El-Sayegh *et al.*, 2020).

Figure 14 Taxonomy of the AM as a whole body of knowledge



Source: Figure by authors

5. Conclusions

Publications on AM have grown strongly over the last 7 years, increasing by a factor of 4 (400% growth). In the last few years, the topic has seen higher growth (not reflected in other previous bibliometric analyses) (Kabir *et al.*, 2020). The growth significantly exceeds the 40% increase in all publications registered in the Scopus database during the same period. It is hypothetically compatible with the reduction of the prices of AM devices, especially those related to FDM technology (Kabir *et al.*, 2020). Also, with the emergence of new materials and AM technologies, new trends in modelling (Tang *et al.*, 2023), the fact that AM is now a highly standardized field (Phillips *et al.*, 2022) and even the use of AM for non-industrial issues such as the creative industries (Abisuga and de Beer, 2023). But this may also be influenced by the emergence of Industry 5.0 because, since 2017, several academic efforts have been pushing the introduction of Industry 5.0 (Demir *et al.*, 2019; Longo *et al.*, 2020; Nahavandi, 2019).

The growth trend in terms of publication volume shows a slight slowdown, which is compatible with the state of maturity of the technology (yet into the mature stage (Kabir *et al.*, 2020)) and the fact that nowadays it is more developed at the business and industrial level (Dzogbewu *et al.*, 2022). Today, AM is a highly standardized topic (Phillips *et al.*, 2022).

The two most important sources in terms of publication volume were the journal Additive Manufacturing (highly specialized in AM) and the journal Materials (oriented towards materials science and technology, but with a wide scope). These journals have also shown the greatest increase in the number of AM-related articles. However, another journal, the International Journal of Advanced Manufacturing Technology, has also shown a significant increase in the number of articles related to AM, similar to Materials. In terms of the knowledge field, journals related to manufacturing processes have increased the production of AM-related articles to a greater extent than journals related to materials science and engineering. However, in the last two years, these differences have narrowed (which may be due to the high growth of the journal Materials).

Segmenting by territory, the authors discovered that the European Union is the territory that has produced the greatest number of articles, followed by the USA, China, and England. However, the trend of journals is not the same in each territory since the journal most chosen by authors for the dissemination of AM-related research was Additive Manufacturing in the USA (12.24%), China (6.47%), and the UK (9.16%). Nevertheless, in the European Union, it was Materials (7.5%).

A Pareto analysis conducted shows that the Pareto Principle holds true in all territories (about 80% of the publications have been made in 20% of the journals). However, compared to other territories, production in China tends to concentrate in a smaller number of journals.

In terms of citation impact, the journal with the highest H-index was Additive Manufacturing, followed by Materials and Design. In general terms, the articles with the highest impact were related to manufacturing and materials science, and a rapid prototyping journal was also detected.

The 25 most-cited papers were individually analysed. The most-cited article reached 699 references per year and was related to the general overview of AM. The AM of metals was a hot topic in seven papers. Looking at the 25 most cited articles, 5 are scientific research articles and 20 are reviews of technological AM processes or articles addressing AM from an economic or market point of view. This is compatible with the novelty and rapid development of AM as a scientific field in engineering and it is also proof of the strong link between additive manufacturing developments (16) and business models and the market (4), with AM having an important economic derivative that currently lacks knowledge (Dzogbewu *et al.*, 2022). Among the trends detected in these articles is the additive manufacturing of metals. This issue has been highly developed in recent years and there are different current review works that address different aspects of AM for metals (C. B. Carolo and Cooper O., 2022; Gong *et al.*, 2023; Orzolek *et al.*, 2022; Slavkovic *et al.*, 2023; Springer *et al.*, 2023; Talignani *et al.*, 2022; Volpato *et al.*, 2022). Some work has already identified this SLM as the most important technology in earlier periods (Kabir *et al.*, 2020).

The biomedical uses of AM reveal another significant trend in the more referenced papers. With the emergence and accelerated integration of AM in the medical and dental fields, the scientific community has become increasingly interested in the subject of research related to the properties of structures manufactured using AM to evaluate them, compare them with classical technologies, and find viable solutions (Moraru *et al.*, 2023). The AM method allows production even with more mechanical properties than the classic methods (Kazemian *et al.*, 2017; Øilo *et al.*, 2018). Finally, another important issue is related to the manufacture of continuous fiber composites using AM. This is an important goal because less complex additive technologies (FDM) can be adapted to manufacture this type of material. However, composites are complex materials, and a multitude of parameters critically affect the quality of the structures (pre-printing set-up, printing factors (materials, machine, process, and environment), and post-printing processing (heat treatment, separation, etc.). (Kabir *et al.*, 2020). Different works have addressed AM in composites (mainly carbon fiber) in recent years (Bermudo Gamboa *et al.*, 2022; Durga Prasada Rao *et al.*, 2019; Ferreira *et al.*, 2017; Wang *et al.*, 2017; Yu *et al.*, 2023).

The affiliations with the highest scientific output were analyzsed. The top 10 produced 28.82% of the total scientific articles. Of the top 10, seven were Chinese affiliations. However, based on the data set evaluated, China is not the country with the highest article production. This indicates that the production of AM-related articles in China is focused on a smaller number of institutions.

The study of collaborations between different affiliations showed that the field of AM is of global interest, and all industrialized countries have done research in the field of AM. It also shows that this type of research is conducted in international collaboration. Analysing the research links separately, the strongest links are between the EU countries, both with the USA and China. Collaborative links between the USA and China are less representative.

The meta-analysis identified three key clusters in AM research. The primary cluster revolves around additive manufacturing of metals and metal material characterization. The second cluster focuses on FDM technology, filament manufacturing, simulation, and Industry 4.0. This cluster can be further divided into two subtopics: one related to FDM technology, thermoplastic extrusion, and composite materials, and another concerning 4.0 / 5.0 Technologies and industry innovations like simulation, optimization, AI, quality, digitalization, and sustainability. Despite its novelty and limited citations, this latter subtopic is gaining importance, especially in integrating AM with AI and quality inspection methods. The third cluster highlights the medical and health applications of additive manufacturing. Moreover, the social and sustainability dimensions of additive manufacturing (AM) are better aligned with the core tenets of Industry 5.0, placing a strong emphasis on human-centeredness, sustainability, and resilience.

Evaluating the relationships between keywords for the main additive technologies among those indicated in ASTM standards and (ISO/ASTM 52900, 2021) (International Organization for Standardization (ISO), 2022)it can be concluded that the links between the SLM method and everything related to the characterization, testing, and manufacturing of metallic materials and alloys. The relationship between material extrusion technology, polymers, and material characterization (in this case, plastics and composites). The relationship between sintering and the structure and characterization of metallic materials. Finally, it was possible to corroborate the low impact of the Vat Photopolymerization technique.

In conclusion, the conducted work indicates that AM is still expanding and developing, albeit at a slower pace due to the technological maturity of many topics and the prevalence of global collaboration. The relationship between AM and Industry 4.0 concepts can constitute a branch of research within AM as a global concept. Furthermore, research connecting AM to the social, environmental, and health domains holds significant importance, indicating a growing relationship between this technology and Industry 5.0 in the upcoming years. Future works address the specific analysis of the integration of 4.0 and 5.0 technologies (like AI or the Internet of Things) within the AM topic.

Finally, it is convenient to indicate that bibliometric analysis presents some methodological limitations, such as the inability of the assessment to consider the fact that citations usually need time to accumulate (more critically when the papers present novelties or disruptive contributions) and that publications in open-access sources may have a citation advantage. Innovative and novel works that have not yet received a high citation frequency in recent years require a more in-depth, systematic review of the content (Zheng *et al.*, 2023). Furthermore, the raw bibliographic data have been extracted from Scopus, which is one of the most wide and important scientific databases in terms of quantity and quality. Since there are other scientific databases, there could be works that are not contemplated in this analysis. However, as long as a statistical approach has been used (and since the papers covered by Scopus represent a very large and possibly unbiased sample of the total population of articles in AM), it is not expected that the essence of the conclusions will differ much if the analysis is reproduced using a different (relevant) database. Despite these limitations, a combination of quantitative bibliometric analysis and qualitative analysis has been applied to the current most-referenced papers to make the conclusions more robust.

Future work will focus on assessing the specific risks of AM in the two contexts: Industry 4.0 and 5.0 in a holistic manner and not on a specific use of AM. Additionally, the specific combination between additive manufacturing and new materials, the circular economy or AI could be the subject of future analysis.

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