Additive manufacturing using Fused Filament Fabrication: evolution and trends

Julian Israel Aguilar-Duque
Universidad Autónoma de Baja California

Jorge Luis Garcia (✉ jorge.garcia@uacj.mx)
Autonomous University of Ciudad Juarez

Juan Luis Hernández-Arellano
Universidad Autónoma de Ciudad Juárez

Abstract

This paper discusses Fused Filament Fabrication (FFF) technology to know their evolution and trends, analyzing the materials, workforce, machinery, methods, and management been used. A literature review is done regarding FFF usage between 2010–2020. Data is analyzed for identify the countries that are applying this technology, the industrial sector, academic resources available and a curve is fitted to data for forecasting a trend until 2025. Projections indicate a growth of 300% for workforce in FFF usage for 2025, 280% for machinery, 312% for materials, 275% for the creation and modification of methods and, 320% growth for management activities.

1. Introduction

The development of manufacturing industry along with the development of new technologies, represents an area of interest concerning the impact that new technologies and the insertion of the Industry 4.0 has in a productive sector. Considering that situation, this research is focused on presenting the advances that the Additive Manufacturing (MA) has had, especially, the Fused Filament Manufacturing (FFF) technology, also known as Fused Deposition Modeling (FDM) due that this technology is the most used in the world [1–4]. This technology has a high acceptance due to low cost in equipment, materials diversity, easy processing, and flexibility in operations [5–8]. FFF has had high impact as a manufacturing process, therefore, this article reports the growth, as well as a synthesis of the AM and FFF technology. Thus, the objective of this article is to present the evolution of the FFF technology under five aspects: materials, manpower, machinery, methods, and management.

1.1 The development of the manufacturing industry and its growth

The manufacturing industry growth along with the incorporation of new technologies represents a challenge for business groups towards 2025, and in such situation, the critical question for manufacturers and investors who must establish priorities regarding the use of resources is: What is the projection of the manufacturing industry growth? [9]. These priorities start from the premise associated with customer satisfaction (focused on service, quality, and unit cost), as well as manufacturer satisfaction (focused on decreasing costs and increasing profits) [10].

Since the growth of the industry has triggered the development of several analyzes that are focused on comparative indexes between the market growth and the development of countries that are immersed in manufacturing activities. According to Organization [11], manufacturing growth by 2025 is projected at 2.7%; reaching up to $18 trillion in a total value and an employment rate growth of up to 590 million.

In order to synthesize the information regarding the market projections made by Economics [12], Table 1 presents the countries with the highest growth in the manufacturing industry according to the market size in millions of dollars. The second column presents the market size in millions of dollars, the third column

presents the projected growth in millions by 2025, and the fourth column shows the corresponding growth percentage.

Similarly, in countries with the highest growth, it is necessary to identify the countries that will have the lowest growth projected by 2025. Table 2 presents the information regarding this classification, where the second column shows the market size in millions of dollars, the third column presents the projected growth in millions for the 2025 years, and the fourth column shows the corresponding growth percentage.

Table 1
Countries with the highest manufacturing growth and their projection on the market growth

Country	Market size (mns)	Market growth to 2025 (mns)	% growth to 2025
China	$ 3,200,063	$ 3,344,065	4.5%
India	$ 356,226	$ 378,668	6.3%
Indonesia	$ 212,778	$223,416	5.0%
Saudi Arabia	$ 79,585	$ 82,847	4.1%
Philippines	$ 59,605	$ 62,764	5.3%
Pakistan	$ 27,474	$ 28,875	5.1%
Vietnam	$ 23,410	$ 25,001	6.8%
Slovenia	$ 8,986	$ 9,336	3.9%
Oman	$ 6,721	$ 6,983	3.9%
Estonia	$ 3,464	$ 3,623	4.6%

Table 2
Countries with slow a manufacturing growth and their market growth projection

Country	Market size (mns)	Market growth to 2025 (mns)	% growth to 2025
Japan	$ 1,241,318	$ 1,252,489	0.9%
Germany	$ 773,661	$ 780,623	0.9%
Italy	$ 296,703	$ 299,670	1.0%
France	$ 285,196	$ 288,047	1.0%
Canada	$ 209,764	$ 212,071	1.1%
Australia	$ 88,817	$ 89,705	1.0%
Venezuela	$ 46,020	$ 46,526	1.1%
Norway	$ 32,983	$ 33,279	0.9%
Chile	$ 26,974	$ 27,189	0.8%
Portugal	$ 27,474	$ 27,748	1.0%

Due to the growth prospects, the manufacturing industry faces new challenges as a result of the products and services diversification, which, due to their constant evolution and innovation are led by the automotive industry. Table 3 presents the comparison of the most developed productive sectors within the manufacturing industry, according to the impact on developments and the number of emerging places participating in the sector [13–19].

Table 3
Comparison of developed and emerging countries

Industry	Developed	Emerging places
Automotive	644	453
Chemicals	520	520
Building materials	180	362
Textiles & Clothing	112	427
Pharmaceuticals	317	191
Precision Instruments	185	46
Machine Tools	175	25
Aerospace	50	17

Note that the dominance of the automotive industry is shown in terms of new products development per year, as well as the number of emerging manufacturing centers participating in these developments. Regardless of the type of manufacturing employed, either a Subtractive Manufacturing (SM) or an Additive Manufacturing (AM), the growth of the manufacturing industry continues to represent a challenge for those involved [20–22, 10, 12].

1.2 Additive manufacturing industry

Because of the appearance of Stereolithography (SLA), which is the first additive manufacturing technology in 1980, the classic process of material subtraction paradigm was broken, enabling the rise of freedom in the design of components and the reduction of classic process stages [23, 22].

Furthermore, the AM is known as a rapid prototyping or 3D prototyping manufacturing that has been characterized as a manufacturing process in which the adhesion of materials layer by layer manages to reproduce or materialize a digital design [24–26]. In official terms and in according to F2792 [27], AM is the "process of joining materials to build objects from a 3D data model, usually layer by layer". The AM implements seven technologies: Sterol lithography (SLA), Fused Filament Fabrication (FFF), Laminate Object Manufacture (LOM), 3D printing (3DP), Selective Laser Sintering (SLS), Laser Engineered Net Shaping (LENSTM), and Electron Beam Melting (EBM), which are selected for their operation depending on the type of material and finish that the user requires [28, 29, 24].

Also, the AM has created high expectations regarding its feasibility dealing with the future of manufacturing processes, which is due to the ease of manufacturing complex components, reducing material waste, and ease of operation. Therefore, growth expectations project a 16% growth in the industrial and professional printers sector by 2020 and a 40% growth in desktop and personal computers for the same year [20]. On the one hand, considering that the growth of the automotive industry rebounds manufacturing, it is necessary to show that AM in the automotive industry currently represents a manufacturing segment with growth expectations in several areas. Figure 1 presents the analysis performed by SmartTech [30] with the subcategories of products generated by the AM for the automotive industry.

Regarding the development of AM considering the regions where it has had the most development [31], can be said that North America have been focused on manufacturing products for advanced aerospace technologies, as well as for the defense sector, in addition to manufacturing metal components and 3D printing for the automotive industry [2, 32]. On the other hand, the direct competition of USA is China, because it has been focused on the development and mass 3D printing for the manufacture of aerospace components [33, 34]. For its part, Europe has been focused on the implementation of AM in naval applications and industrial components [30, 22, 31, 23].

As a result, it is important to present the projections of the AM that have a positive trend, for example, it will grow approximately by 15% between 2020 and 2025. The participation of the AM in the automotive industry will be 36% more for 2020–2025, 51% in participation for the aerospace and medical industry,

and 23% for the printing of different types of devices [35, 11, 2, 3, 22]. Growth projections by region in trillions of dollars are presented graphically in Fig. 2.

1.3 Additive Manufacturing and Fused Filament Fabrication technology

The Fused Filament Fabrication (FFF) also called Fused Deposition Modeling (FDM) is an additive manufacturing process that uses filament as a row material [36]. This technology works extruding liquid thermoplastic. The thermoplastic liquid is first over heated in an extruder, then is deposited in a "hot" flat bed. The term "hot" is between quotation marks because not all the materials used by this technology requires the flat bed to be in a high temperature to print a component.

In FFF, the user first creates a design using a special design software. After the design is complete, it is saved as an .STL file to be loaded in an interfacing software of the FFF equipment. The interface uses a software to converts the file and slices the model into sections, as well as determines a group of instructions to establish how the layers will be printed. After the instructions are sent to the printer, the build material is extruded through a heated nozzle by layer until the part is completed [37].

Due to the facility to operate FFF equipment and the low cost that it represents for users, FFF technology has become a AM technology with one of the most economic gains implementing the printing hardware that has the highest growth projection in the field with a profit of $550 billion dollars for printers and hardware by 2025 [20, 21]. In order to expose the impact of the FFF technology, Fig. 3 presents the growth graphically corresponding to the comparison between 2020 and 2021.

Moreover, due to the growth projections of the AM, it is important to identify the needs that manufacturers will have to solve in the demands of qualified personnel [4, 38, 39], more efficient printing equipment [40, 41], materials with innovative characteristics [42−44], as well as the actions by efficient management of the FFF process [23, 45, 46]. Therefore, this article analyzes the growth and development of this technology, which, based on the information obtained, makes a projection about the growth of some aspects: manpower, materials, machinery, methods, and management, as well as the recommendations to solve these types of needs.

2. Methodology

The methodology is implemented to identify the evolution of the FFF, which is the proposed by Gómez-Luna et al. [47]. Figure 4 presents the diagram of the three phases that are used in the methodology.

Since the interest in the evolution and trends of the FFF is focused on five factors (manpower, machinery, materials, methods, and management), two syntaxis are considered. Specifically, the two syntaxis are integrated by the combination of the five aspects that were previously mentioned, as well as the name of the technology that is implemented (FFF or FDM). In addition, for the search, review, and analysis of the information databases, internet publications, internet sites, and news were considered.

1. Phase 1 Information search. This phase is focused on the process of information collection. The sources considering were the following data bases: Springer, Science Direct, Emeraldinsight, and EBSCO. The internet sites considered were: www.additivemanufacturign.com/category/news, www.materialstoday.com/additive-manufacturing/news/, www.tctmagazine.com/3d-printing-services-bureaux-news, and www.additivemanufacturingtoday.com. The research syntax was integrated in first term by the words "Fused Filament Fabrication" and "Fused Deposition Modeling" in combination with the words "machine develop", "materials develop", "methods develop", "manpower develop/influence" and, "management develop". The period of research is restricted from 2010 to 2020.
2. Phase 2 Information organization. Because the AM technology interest is FFF or FDM, the classification considers five categories: manpower, machinery, methods, materials, and management. In order to consider a resource that must be integrated in the manpower category, the information describes skills, knowledge, and experience. For the machinery category, the documents considered describes the modification of at least one component in the printer. In the case of materials, the information contains the description filament and components. Finally, management category is associated to the supply chain, facilities, and the resources that are indirectly related with the FFF process.
3. Phase 3 Analysis of the information. The last phase is focused on analyze the information, the record of the results generated by this search are deployed considering the manpower, machinery, materials, methods, and management categories. The structure used in each category is integrated by a table with the results of the bibliography and websites research, a graph with the tendency of the results mentioned, and finally a synthesized discussion about the results.

3. Results

3.1 Manpower

Users of the FFF equipment generally are familiar with design or engineering knowledge, because the use of printing equipment requires a basic knowledge for generating a printed element in FFF. Specifically, FFF equipment users can be divided into designers or engineers for the stage related to the component design. 3D printer designers, engineers, or technicians in operation are required for the component printing stage and the inspection process, and technicians are needed for the component finishing stage. Table 4 presents the results of the bibliographic and database search subjected to the "Fused Filament Fabrication and Manpower" and "Fused Deposition Modeling and Manpower" syntax.

Table 4
Results from the bibliographic and websites research using the Fused Deposition
Modeling, Fused Filament Fabrication, and Manpower terms

Resource	Number of coincidences
www.additivemanufacturingtoday.com	75
www.additivemanufacturign.com/category/news	53
Science Direct	50
www.tctmagazine.com/3d-printing-services-bureaux-news	29
Springer	27
www.materialstoday.com/additive-manufacturing/news/	11
Emeraldinsight	1
EBSCO	1

Considering the results obtained by searching the databases and the most influential and dominating sites on the subject of Fused Filament Fabrication associated with workforce, it is possible to identify that the combination of the two key terms present a growing trend (See Fig. 5), that is, during the last ten years, the issue associated with trained personnel and the handling of printing equipment through FFF technology has received special interest among researchers from social, humanity, and engineering fields that have been focused on the skills and knowledge that the management and operation of FFF equipment demands.

Considering the fit of the proposed model with a determination coefficient of 93.92%, it is expected that the development of publications based on the use of the Fused Deposition Modeling, Fused Filament Fabrication and Manpower syntax are focused on the skills required for the industry grow according to Table 5.

Table 5
Projection of publications for the
next six years

Year	Number of publications
2020	121
2021	154
2022	191
2023	232
2024	277
2025	325

Among the results obtained by the search, the term applied technology skills (ATS: Applied Technology Skills) is prominent, which are described as the skills that integrate people, processes, data, and devices that are useful for the operation of new technologies as well as their efficiency as a business strategy [10, 48, 49].

The projection of the skills required by 2030 according to Institute [50] are summarized in:

- **Demand for technological skills**, both basic digital skills (knowledge on digital world, network monitoring, communication in digital environments, networking, knowledge recycling, global vision, and customer service) and advanced technological skills (quantitative analysis of data or regressions, intelligence Artificial, Cloud Computing, Data Scientist, Engineering and Data Warehousing, Metadata Design and Development base), all with a projected growth in demand of 55% by 2030.

- **Demand for social and emotional skills**, employees are expected to have the social skills (active listening, assertiveness, emotional validation, empathy, negotiation skills, respect, credibility, compassion, positive thinking, emotional regulation, open-mindedness, patience, courtesy, and ability of expression), emotional skills (self-control, self-knowledge, positive thinking, empathy, and assertiveness), and leadership, which projects a development of 24% growth by 2030.

- **Demand for basic cognitive skills**, it refers to attention, memory, self-awareness, reasoning, motivation, association capacity, cognitive flexibility, and problem solving, which with the development of new technologies their demand decrease in more than 15% by 2030.

- **Demand for manual and physical skills**, known also as endurance, strength, speed, flexibility, agility, and power, which tend to decrease in 14% due to the design of the tasks, consequently, they tend to reduce elements that generate fatigue and stress.

- On the one hand, the nature of the man-machine relationship that in the case of this research is a printer-operator relationship, the required skills are focused on manual skills that are required for the

process of preparing and adjusting the printing equipment, a demand for cognitive abilities associated with homework attention and reasoning for problem solving. On the other hand, a specialized knowledge development that is focused on technological skills is required, since the operation of the equipment interface represents the ability to manage computer equipment, data management, and use of the network, which in contrast to the demand for social skills practically does not exist, because the user interaction with others is reduced to the exchange of only specific information.

3.2 Machinery

The development of new printing equipment has grown rapidly in recent years. The FFF equipment manufacturers have focused their efforts on improving equipment characteristics along with reducing costs. [51, 21, 22, 31]. Aiming to improve the quality of printed components, the new equipment features: high-quality and low-cost of components [23, 52, 36]. Table 6 presents the results obtained by searching for data associated with the combination syntax between "Fused Filament Fabrication and machinery" and "Fused Deposition Modeling and machinery".

Table 6
Results from the bibliographic and websites search using the Fused Deposition Modeling, Fused Filament Fabrication and machinery terms

Resource	Number of coincidences
Springer	3109
Science Direct	2389
EBSCO	1256
www.additivemanufacturign.com/category/news	353
www.materialstoday.com/additive-manufacturing/news/	253
Emeraldinsight	246
www.tctmagazine.com/3d-printing-services-bureaux-news	190
www.additivemanufacturingtoday.com	146

The growth of the FFF technology has led to the development of new research as well as reports on research journals and specialized web sites. To evidence the growth, Fig. 6 presents the records on the growth in terms of the FFF teams' development. Also, it is possible to project with a coefficient determination of 98.59% a significant growth in terms of the number of developments registered in research sources. Table 7 shows the projection of publications expected for the next six years.

Table 7
Projection of publications for the development of FFF technology machinery

Year	Number of publications
2020	2989
2021	3655
2022	4388
2023	5188
2024	6054
2025	6986

The operation of an FFF printer is led by a simple method that is based on three main elements: a flat bed or printing plate in which the material is deposited to form the impression, a roll of raw material known as filament, and finally an assembly called extruder, which is made up of a nozzle, a motor, temperature generation elements, and temperature control elements.

Moreover, the evolution of the FFF printing equipment can be described as one of the most important achievements throughout its short history according to Savini, Savini [53].

- 1980 first development of the Cast Filament Printing equipment by Scott Crump.
- 1990, Fused Deposition Modeling or Fused Filament Fabrication 3D printers begin with the "Printing equipment at everyone's reach" marketing stage.
- 2005, the Rap Rap movement begins, which consists of opening operating codes of printing equipment to the community, this opening of codes and resources involves pre-manufacture printer components, component designs on web platforms to be replicated, operation and preparation of codes that are used in the pre-process stages.
- 2009, the patent registration of the first FDM print expires, thereby, achieving the opening and development of new companies in charge of replicating the printing technology for molten filament. Currently, brands diversify, as a result, the sale prices of printing equipment and expanding the offer of these equipment decrease.
- Since the commercialization of printing equipment, developers have entered the competition to attract a larger market. Concerning this growth and development, the best printing equipment and its characteristics are advertised annually. The results obtained from the evaluation of the FFF printing equipment by Hanson [54] are presented in Table 8.
- As it is mentioned, the development of printing equipment allows FFF printing technology to be more accessible to the market, managing to provide manufacturing equipment at low cost (from 200 US),

with printing formats for 150 mm3 components, a low cost, and with an acceptable resolution (between 50 and 400 microns).

Table 8
The best FFF printer from January 2020 [54].

Name	Characteristics	Advantages	Disadvantages
XYZ printign da Vinci Mini+	Printing area 150x150x150mm. Minimum layer resolution 100 microns, maximum layer resolution 400 microns. Dimensions 390x335x360 mm. Weight 6.85 kg	Low price $ 173.20 US Easy operation	The design of the printer makes it difficult to remove the printed object
Ultimaker 2+	Filament diameter: 2.85. Printing area 223x223x305mm. Minimum layer resolution 20 microns, maximum layer resolution 600 microns. Dimensions 342x493x588 mm. Weight 11.3 kg	Leader in the field of print quality. Easy networking operation	Expensive $ 3,000 US
Crazy3DPrint CZ-300	Printing area 300x300x300mm. Minimum layer resolution 100 microns, maximum layer resolution 400 microns. Dimensions 534x503x582 mm. Weight 16.5 kg	Low price $249 US Easy operation Large printing platform	
Prusa i3 MK3s	Printing area 250x210x210mm. Minimum layer resolution 50 microns, maximum layer resolution 350 microns. Dimensions 550x400x500 mm. Weight 7.00 kg	High print speed Market leader for print quality	Open frame design Price $ 1,000
LulzBot Mini 2	Printing area 160x160x180mm. Minimum layer resolution 50 microns, maximum layer resolution 400 microns. Dimensions 457x339x607, mm. Weight 6.85 kg	Easy operation Open source	Open frame design Price $ 1,375
Cel RoboxDual	Printing area 210x150x100mm. Minimum layer resolution 50 microns, maximum layer resolution 500 microns. Dimensions 410x340x240, mm.	Easy operation Trustworthy Low price $287 US	Requires filament with specific characteristics
Trilab DeltiQ2	Printing area 250x250x300mm. Minimum layer resolution 50 microns, maximum layer resolution depends on the nozzle. Dimensions 410x500x810, mm. Weight 10.0 kg	New technological era in printing equipment. Versatile Expandable	Complex machine

3.3 Materials

Printing materials are other of the most interesting elements involved in the development of FFF technology. Since its inception, the use of filament or thread has become the main characteristic of printing equipment, because the shape of the material is the only one that has undergone two changes, as well as having the presence of only two dimensions of material in the market: 1.75 mm and 2.85 mm. In the search for information associated with this factor in the FFF industry, it is possible to identify that along with the development of printing equipment, materials are the most developed factor in the field of research. Table 9 presents the results of the search based on the syntax between "Fused Filament Fabrication and materials" and "Fused Deposition Modeling and materials."

Table 9
Results of the bibliographic and websites research using the Fused Deposition Modeling, Fused Filament Fabrication and materials terms

Resource	Number of coincidences
Science Direct	2321
Springer	987
EBSCO	730
Emeraldinsight	416
www.additivemanufacturingtoday.com	207
www.materialstoday.com/additive-manufacturing/news/	163
www.tctmagazine.com/3d-printing-services-bureaux-news	107
www.additivemanufacturign.com/category/news	100

Because of the materials development, it is possible to discard that the applications of greater focus are those that are used by the medical industry. In these applications the main focus is identifying publications concerning with the density of the polymer, the transition value associated with the temperature transition, resistance characteristics (Young's modulus), the tensile strength, the elongation point up to the break, the limit temperature defined for the decomposition point, and the ideal operating temperature.

In addition, it is evident that the materials development presents an ideal alternative for the growth of the printing industry using FFF technology. Figure 7 presents the evidence of this growth, where an exponential growth associated with the generation of results is observed, subjected to the search syntax "Fused Deposition Modeling and materials" and "Fused Filament Fabrication and materials."

Based on the proposed model, the projection of the formally identified research resources for the next six years can be made. Table 10 shows the corresponding projection with a coefficient determination of 97.33%.

Table 10
Projection of research resources published for 2025 about the FFF and materials syntax

Year	Number of publications
2020	1871
2021	2341
2022	2866
2023	3444
2024	4077
2025	4764

The rapid development of the materials that are implemented in the FFF has different needs of users. Specifically, the use of polymers, such as PLA (Polylactic acid) and ABS (acrylonitrile butadiene styrene) are related to the attribute of hardness, in this sense, ABS is more rigid, therefore, the selection of this material depends on the model print that is subjected to high stresses.

On the other hand, the implementation of PLA is defined by the characteristics of the process, in which it is not necessary to isolate the process during the printing stage, since the material does not present changes when it is in contact with the environment during the printing process, while for the implementation of ABS, it is required to be isolated from the environment and with a controlled temperature during the printing process. In addition, under these circumstances, the development of materials has achieved a significant growth depending on the function the prototype is subjected and to the printing process. In order to synthesize the development of materials, their applications, and characteristics, Table 11 presents the materials implemented in the existing FFF processes and available for users by 2020 according to Technologies [55].

As it is previously mentioned, the development of materials implemented by the FFF technology is the area where the most developments have been registered, thereby, it provides the possibility of producing prototypes with different characteristics, mainly physical and mechanical.

Table 11
The best FFF materials from January 2020 [55].

Material	Applications	Features
Hydretel 3D4000FL	Useful for all wire and cable manufactures It can be used as a copper insulation and fiber optics cable Ideal for making automotive chassis suspension system parts Flexibility, can be starched bidirectionally for maximum body weight distribution.	Halogen free Corona resistant Excellent resistance to flex fatigue Great performance in oil ad wide range materials Flexible with lower temperature range (35°C, -35°F. Capable to work in higher temperature range (160°C, 320°F)
Hydretel 3d4100FL	Resistant impact in plastics with UV stability Lower weight Capable to work with lower higher temperature resistance Flexibility after printing.	Resistance to damage caused by twisting and flexing Light weight strength Easy to print Low warpage and shrinkage Chemical resistance with strength Superior durability

Material	Applications	Features
Zytel Nylon Polymer	Mobile phone housing and components Gaming Laptop and Tablet parts Can be used as a wire insulation	Halogen free Versatile Great moisture and abrasion resistance High quality finishing Decrease shocks Absorb vibration Reduce wear
Carbon Fiber Nylon	Ideal for structural components high modulus. Improved chemical resistance Improved thermal resistance Excellent surface quality Ease of printing	High modulus Carbon Fiber Semi aromatic polyamide Lower moisture uptake Improve chemical resistance Less shrinkage Low gloss surface
Wax	Can be used for printing mold and it features an excellent dimension stability 3D Lost wax casting Allows to create dental molds & produce customizable jewelry of very high quality	Easy formability Good machinability Ductile Superior Surface Quality Clean Burnout

Material	Applications	Features
Polymethyl methacrylate	Its translucency and transparency make it the ideal solution where a clear part or object is the desired result	Excellent finish quality and clarity
		Responds very well to post print finishing
		Pure resin quality
TitanX	Ideal for applications that request high exhaustion perseverance	Warp-free
		Optimized filament flowing behavior
		Excellent adhesion to heated glass plate
		Greatly improved mechanical properties and strength
		High impact resistance
ApolloX	Used for outdoor-aerospace and automotive applications	UV resistant
		Warp free printing
		Thermal stability
		Extremely high printing precision
PC Plus	Ideal for applications that require though mechanical properties.	Mechanical strength
		Heat resistance
		Optical Clarity
		Good chemical solvent resistance

Material	Applications	Features
Alloy 910	Used to print frames, enclosures, parts that requires high strength and stiffness. Used in 3d forging, prosthetics, robotics, assemblies, jewelry printing.	High tensile profile Constant strength under stress Chemical resistance of a nylon Certified for use in food handling
Plasticized Copolyamide TPE	Used to prints farts from solid prosthetics to complete cosplay wearable outfits, cell phone enclosures and highly flexible utility and mechanical parts.	High sturdy and durable material It can handle stress at elevated temperatures Wearable texture Lustrous texture Flexibility
Policarbonate	Useful in prototyping application where sheet metal lacks transparency, non-conductivity and insulation. Used in medical industry, automotive industry, electric and electronics, machinery, safety, office automatization equipment, household applications, optical and communications.	High impact strength High temperature resistance Less than half the density of glass Light weight Machine bendable at room temperature Extremely durable Nonconductive Reduces glare

Material	Applications	Features
Transparent PLA	Used in transparent 3d models	Transparent clear finish High strength High toughness High temperature resistance
Nylon	Is used in applications that request high exhaustion perseverance. Is used in aerospace and automotive applications	Higher strength Extremely durable polymer It handles stress at elevated temperatures.
Acrylonitrile Butadiene Styrene	It can be used to make lightweight, solid modeled products.	Strong and has high melting point Mechanically strong and stable overt time Very high impact strength & high tensile strength and stiffness Good chemical resistance Dimensional stability Water permeable.

Material	Applications	Features
Polylactic Acid	Is used in food packing, bags, disposable tableware, upholstery, disposable garments, hygiene products.	Transparent Strong Ideal for small parts Becomes soft around 50°C
High Impact Polystyrene	Is used for low strength structural applications such as housing and covers.	Good impact resistance Excellent machinability Good dimensional stability Easy to sand, paint and glue Low cost FDA compliant Low shrinkage value Light weight
Polyvinyl alcohol	Is used as a supportive material with PC, ABS and PLA to get high resolution prototypes where aesthetics cannot be compromised. Is used generally in applications where plastic needs to be dissolved as a supportive material as a binding agent.	Water soluble Incompressible and heat resistant Low elongation and low flexible High modulus and good durability Improve layer hardness Nontoxic

3.4 Methods

Unlike the rapid growth and development in the field of FFF materials and technology, research development has been focused on the methods implemented, but it has not evolved much in the past ten years. Table 12 presents the results of the matches obtained using the "Fused Deposition Modeling and methods" and "Fused Filament Fabrications and methods" syntax.

Table 12
Results from the bibliographic and websites research using the Fused Deposition Modeling, Fused Filament Fabrication and methods terms

Resource	Number of coincidences
Science Direct	2249
Springer	694
Emeraldinsight	404
EBSCO	234
www.materialstoday.com/additive-manufacturing/news/	53
www.tctmagazine.com/3d-printing-services-bureaux-news	37
www.additivemanufacturingtoday.com	35
www.additivemanufacturign.com/category/news	23

The results obtained from the databases and the internet sites identify variations in the methods, mainly based on the use of software for designing and pre-processing, optimization strategies of the component related to variations in the filling, orientation, and printing of the component, as well as to the follow-up activities of the printing process and post process.

In fact, with the results obtained from the bibliographic search and from the database, the graph in Fig. 8 is developed, which shows a clear trend towards the development of new methods applied to the FFF technology. It is worth mentioning that the modifications and records found are focused on small modifications and the use of instruments to adjust the principal equipment for the printing process.

According to the proposed model, it is possible to make a projection of the possible publications for the next six years. Table 13 was developed with a coefficient determination of 98.59%.

Table 13
Projection of research resources
published for 2025 from the FFF
and methods syntax

Year	Number of publications
2020	1337
2021	1649
2022	1993
2023	2371
2024	2783
2025	3228

In general, the method is used to manufacture components applying FFF technology, which is summarized in five stages. The first stage begins with the design and development of the part or component using a specialized design software, such as SolidWorks® [56], or Autocad® [57], among others. At this stage, computer-aided design and computer-aided engineering allow the designer to perform feasibility, strength, shape, and material analysis digitally on the designed element.

The second stage of the process consists of preparing the elements to be printed using a pre-process software, such as Repetier® [58], Cura® [59], or Makerbot® [60]. In this stage, the extension file must be imported in .STL (Standard Triangle Language) and specify the desired manufacturing properties, such as type of material, orientation, quality, resistance, among others.

The third stage is associated with manufacturing, in this stage the strength attributes associated with the type of material that is used and the quality of finish must be defined. Once the component is manufactured, the user decides to give the final finish, this is the fourth stage, therefore, the component is subjected to some processes for extracting excess material, applying layers or paint, among others.

Finally, in case of a batch small production with a different approach for prototyping, the manufacturer can perform quality inspection tests in the shipment for the final user, and in case that they are prototyping elements, the components are sent to the laboratories or to the research and development centers for their use. Figure 9 presents schematically the method that is used in the manufacture of components through the FFF technology, with the steps previously described.

3.5 Management

Regarding the management concept used as one of the five factors of the FFF technology development, the term of management has been directed, according to the results obtained, towards the impact that the use of technology will have on the supply chain. It has recently been identified that companies that implements this technology have started to create and manufacture a wide range of articles with new

shapes, in which the versatility of the material, the quality of the printed component, the response times, as well as the component design flexibility is beyond the traditional production system. The management factor compared to the other four factors is the one that has the least evidence of publications associated with database and technological platforms. Table 14 shows the results that has been published during the last decade.

Table 14
Results from the bibliographic and websites research using the Fused Deposition Modeling, Fused Filament Fabrication and management terms

Resource	Number of coincidences
Science Direct	399
www.additivemanufacturingtoday.com	207
www.materialstoday.com/additive-manufacturing/news/	163
Springer	122
Emeraldinsight	110
www.tctmagazine.com/3d-printing-services-bureaux-news	107
www.additivemanufacturign.com/category/news	100
EBSCO	33

Despite the limited evidence about administration, the fifth factor from the FFF technology development tends to continue evolving. To proof this, the results of the publications are presented in Fig. 10.

The projections are optimistic regarding the modification of the supply chain due to the use of MA technologies, as well as the development of 3D printing within the new age of manufacturing. However, it must be established that manufacturing through FFF or any of the other AM technologies will immediately replace traditional manufacturing processes along with all the strategies established to achieve the administration of classic manufacturing systems.

In addition, the use of the FFF requires a management system that is not really different from the one that is used in the subtractive industry, in this case, the AM literature review and websites research, especially related to the FFF, demonstrate that the independence of the equipment makes the system manufacturing more agile, which is due to the amount of human resources that must be managed to achieve the printing of a component, the process of acquiring materials for printing, after-sales activities that are required in case the organization of printing through FFF needs them, as well as the minimum activities required for the FFF technology to operate properly from an individual manufacturing point of view to a small-scale manufacturing perspective.

According to the proposed model, it is possible to make a prediction about what is expected for the next six years, the results obtained are presented in Table 15, which have been estimated with the constructed model with a coefficient determination of 98.55%.

Table 15
Projection of research resources published for 2025 from the FFF and management syntax

Year	Number of publications
2020	315
2021	391
2022	474
2023	566
2024	666
2025	774

Finally, the administration activities of a single printing equipment are reduced to the administration of a single human resource, who has the capacity to perform all the required tasks to achieve the operation of the FFF equipment for a customized printing or low scale. This inherently projects the growth of the skills required by 2030 for FFF users, as well as a manufacturing system with a less complex and cheaper management structure.

4. Conclusions

The development of this section is exposed based on the five elements that were analysed during the development of this research: manpower, machinery, materials, methods, and management.

Regarding the workforce, the development of FFF tends to demand people with basic digital skills, the exchange of information, and the management of network information, since the operation of the FFF equipment is carried out through internal networks. Specially, it requires personnel with the ability to solve problems that are generated by the operation of the equipment and process failures, which do not require a high physical effort, but intermediate manual skills are needed.

Moreover, the development of printing equipment was diversified from the commercial opening with the expiration of the first patent. The opening has led to the equipment that is currently available to a larger market, at a low cost, with basic operating characteristics, as well as with characteristics of average layer quality between 50 and 400 microns. These attributes allow users to make higher quality developments, and in some cases, smaller production of batches.

The development of materials for the FFF technology has been favored with a significant growth because of the appearance of this type of technology, which initially had two substrates: PLA and ABS. Currently, the development of materials is an area of opportunity in which there are more than 10,000 different types of materials, which is why it is updated on the needs concerning the prototyping of new components.

In addition, unlike materials, the method is one of the items that has not evolved much regarding the FFF technology. However, the records show that both researchers and users have made a constant effort to improve the way in which they obtain their components. It is worth mentioning that the literature review found as evidence of improvements in the method, which is basically scarce compared to the information available on digital platforms and social networks, consequently, there is the possibility of making a formal record on the improvements despite that the improvements that are developed have a short life cycle caused by the rapid development of technology.

Finally, the factor associated with the administration of projects applying FFF tends to develop a simpler and cheaper management model of the productive systems, because of the team's autonomy and the skills that the users must have for the operation of a sustainable system. Also, the present analysis is a study that considers the current state of the FFF technology, therefore, the development and growth of this type of technology is available for the development of technological factors, as well as for the impact that FFF has on new manufacturing systems.

Declarations

References

1. Wirth M (2020) What the 3D Printing Community Teaches Us About Innovation. The Crest of the Innovation Management Research Wave. vol Series in Innovation Studies. Vernon Press, Malaga

2. Nikitakos N, Dagkinis I, Papachristos D, Georgantis G, Kostidi E (2020) Economics in 3D printing. In: 3D Printing: Applications in Medicine and Surgery. Elsevier Inc., pp 85–95. doi:https://doi.org/10.1016/B978-0-323-66164-5.00006-4

3. McCormick H, Zhang R, Boardman R, Jones C, Henninger CE (2020) 3D-Printing in the Fashion Industry: A Fad or the Future? In: Technology-Driven Sustainability. Springer, pp 137–154. doi:https://doi.org/10.1007/978-3-030-15483-7_8

4. Woodson T, Alcantara JT, do Nascimento MS (2019) Is 3D printing an inclusive innovation?: An examination of 3D printing in Brazil. Technovation 80–81:54–62. doi:https://doi.org/10.1016/j.technovation.2018.12.001

5. Taha MM, Jumaidin R, Razali NM, Kudus SIA (2020) Green Material for Fused Filament Fabrication: A Review. In: Implementation and Evaluation of Green Materials in Technology Development: Emerging Research and Opportunities. IGI Global, pp 1–27. doi:https://doi.org/10.4018/978-1-7998-1374-3.ch001

6. Armoo AK, Franklyn-Green L-G, Braham AJ (2020) The fourth industrial revolution: a game-changer for the tourism and maritime industries. Worldwide Hospitality Tourism Themes 12(1):13–23. doi:https://doi.org/10.1108/WHATT-10-2019-0063

7. Shanmugam S, Naik A, Sujan T, Desai S, Developing Robust 3D Printed Parts For Automotive Application Using Design For Additive Manufacturing And Optimization Techniques. In: INCOSE International Symposium, 2019. Wiley Online Library, pp 394–407. doi:https://doi.org/10.1002/j.2334-5837.2019.00694.x

8. Nachal N, Moses J, Karthik P, Anandharamakrishnan C (2019) Applications of 3D Printing in Food Processing. Food Eng Rev 11(3):123–141. doi:https://doi.org/10.1007/s12393-019-09199-8

9. Group WB (2019) The World Bank Indicators [In spanish: Indicadores del Banco Mundial]. https://data.worldbank.org/topic/private-sector?view=chart. Accessed 02.17.2020 2018

10. Karwowski W, Trzcielinski S, Mrugalska B, Di Nicolantonio M, Rossi E Advances in Manufacturing, Production Management and Process Control. In: AHFE International Conference on Advanced Production Management and Process Control, Washington, D.C. U.S.A., 2019. Springer, p 506. doi:https://doi.org/10.1007/978-3-319-94196-7

11. Organization WT (2019) Global value chain development report 2019. Technologicla innovation, supply chain trade, and workers in a globalized world. 2019 edn. World Trade Organization, Geneva, Switzerland

12. Economics O (2020) The Future of Global Manufacturing, vol 1. Oxford Economics, Oxford

13. Aerospace E (2019) Aerospace News. Essentra Components. https://www.essentracomponents.com/en-us/news/industries/aerospace. Accessed 2020.01.09

14. Automotive E (2019) Automotive News. Essentra Components. https://www.essentracomponents.com/en-us/news/industries/automotive. Accessed 20.01.09 2020

15. Construction E (2019) Construction News. Essentra Components. https://www.essentracomponents.com/en-us/news/industries/construction-and-mining. Accessed 2020.01.09 2020

16. Electronics E (2019) Consumer Electronics. Essentra Components. https://www.essentracomponents.com/en-us/news/industries/consumer-electronics. Accessed 2020.01.09 2020

17. Machine EI (2019) Industrial & Machine. Essentra Components. https://www.essentracomponents.com/en-us/news/industries/industrial-and-machine. Accessed 2020.01.09 2020

18. 4.0 EI (2019) Indsutry 4.0. Essentra Components. https://www.essentracomponents.com/en-us/news/industries/industry-40. Accessed 2020.01.09 2020

19. Chemicals EO (2019) Oil and Chemicals. Essentra Components. https://www.essentracomponents.com/en-us/news/industries/oil-and-gas. Accessed 2020.01.09 2020

20. Belman E, Jiménez J, Hernández S (2020) Comprehensive analysis of design principles in the context of Industry 4.0. Revista Iberoamericana de Automática e Informática Industrial, vol 1. Universitat Politecnica de Valencia, Valencia, Spain. doi:https://doi.org/10.4995/riai.2020.12579

21. DDDrop (2020) What are the advantages of the FDM technology? https://www.dddrop.com/fdm-technology/. Accessed 02.05.2020 2020

22. MarketWatch I (2019) Additive Manufacturing Market Industry 2019 Global Growth, Size, Demand, Trends, Insights and Forecast 2023. MarketWatch. https://www.marketwatch.com/press-release/additive-manufacturing-market-industry-2019-global-growth-size-demand-trends-insights-and-forecast-2023-2019-09-18. Accessed 2020.01.07 2020

23. Petch M (2018) 3D PRINTING INDUSTRY JOBS BOARD LAUNCHES. 3D Ptinting Industry. https://3dprintingindustry.com/news/3d-printing-industry-jobs-board-launches-130004/. Accessed 2020.01.15 2020

24. Jones JB, Wimpenny DI, Gibbons GJ (2015) Additive manufacturing under pressure. Rapid Prototyping Journal 21(1):89–97. doi:https://doi.org/10.1108/rpj-02-2013-0016

25. Mellor S, Hao L, Zhang D (2014) Additive manufacturing: A framework for implementation. Int J Prod Econ 149:194–201. doi:https://doi.org/10.1016/j.ijpe.2013.07.008

26. Campbell I, Bourell D, Gibson I (2012) Additive manufacturing: rapid prototyping comes of age. Rapid Prototyping Journal 18(4):255–258. doi:http://doi.org/10.1108/13552541211231563

27. F2792 A (2013) Standard Terminology for Additive Manufacturing Technologies. International Standard Organization, Geneva 20, Switzerland. doi:https://doi.org/10.1520/f2792-12a

28. Srivatsan TS, Sudarchan TS (2016) Additive Manufacturing. Innovations, Advances, and Applications, vol 1. 1 edn. Taylor & Francis, Boca Raton First published

29. Bourell D, Beaman JJ, Marcurs HL, Barlow JW (1990) Solid Freform Fabrication An Advanced Manufacturing Approach. In: Austin TUoTa (ed) International Solid Freeform Fabrication

Symposium, Austin USA, 1990. 1990 International Solid Freeform Fabrication Symposium. Austin, U.S.A., p 7. doi:https://doi.org/10.15781/T2W08X029

30. SmartTech (2019) Additive Manufacturing Opportunities In Automotive. SmartTech. https://www.smartechanalysis.com/reports/automotive-additive-manufacturing/. Accessed 03.17.2020 2020

31. 3Dnatives (2019) Context Figs. 42% growth in the 3D printing sector by 2021. 3Dnatives SAS. http://imprimalia3d.com/noticias/2017/05/11/009050/context-cifra-42-crecimiento-del-sector-impresi-n-3d-2021. Accessed 2020.01.15 2020

32. Heemsbergen L, Daly A, Lu J, Birtchnell T (2019) 3D-printed futures of manufacturing, social change and technological innovation in China and Singapore: the ghost of a massless future? Science Technology Society 24(2):254–270. doi:https://doi.org/10.1177/0971721819841970

33. Zhang L, Luo X, Ren L, Mai J, Pan F, Zhao Z, Li B (2020) Cloud based 3D printing service platform for personalized manufacturing. Science China Information Sciences 63(2):124201. doi:https://doi.org/10.1007/s11432-018-9942-y

34. Wang L, Du W, He P, Yang M (2020) Topology Optimization and 3D Printing of Three-Branch Joints in Treelike Structures. J Struct Eng 146(1):04019167. doi:https://doi.org/10.1061/(asce)st.1943-541x.0002454

35. Jiang J, Qu L (2020) Changes in Global Trade Patterns in Manufacturing, 2001–2018. American Journal of Industrial Business Management 10(5):876–899

36. Esposito Corcione C, Palumbo E, Masciullo A, Montagna F, Torricelli MC (2018) Fused Deposition Modeling (FDM): An innovative technique aimed at reusing Lecce stone waste for industrial design and building applications. Constr Build Mater 158:276–284. doi:https://doi.org/10.1016/j.conbuildmat.2017.10.011

37. Crump C (1999) Apparatus and method for creating three-dimensional modeling data from an object. U.S.A. Patent

38. Flynn EP, Bach C, Integrating Advanced CAD, Modeling Simulation, 3D Printing, and Manufacturing into Higher Education STEM courses. In: 2019 IEEE Technology & Engineering Management Conference (TEMSCON) (2019) IEEE, pp 1–5. doi:https://doi.org/10.1109/TEMSCON.2019.8813627

39. Ford S, Minshall T (2019) Invited review article: Where and how 3D printing is used in teaching and education. Additive Manufacturing 25:131–150. doi:https://doi.org/10.1016/j.addma.2018.10.028

40. Hamidi F, Aslani F (2019) Additive manufacturing of cementitious composites: Materials, methods, potentials, and challenges. Constr Build Mater 218:582–609. doi:https://doi.org/10.1016/j.conbuildmat.2019.05.140

41. Bogdanov D (2019) 3D Printing Technology as a Trigger for the Fourth Industrial Revolution: New Challenges to the Legal System. Perm U Herald Jurid Sci 44:238. doi:https://doi.org/10.17072/1995-4190-2019-44-238-260

42. Weng Y, Li M, Liu Z, Lao W, Lu B, Zhang D, Tan MJ (2019) Printability and fire performance of a developed 3D printable fibre reinforced cementitious composites under elevated temperatures.

Virtual Physical Prototyping 14(3):284–292. doi:https://doi.org/10.1080/17452759.2018.1555046

43. Arivarasi A, Kumar A (2019) Classification of challenges in 3D printing for combined electrochemical and microfluidic applications: a review. Rapid Prototyping Journal 25(7):1328–1346. doi:https://doi.org/10.1108/RPJ-05-2018-0115

44. Herzberger J, Sirrine JM, Williams CB, Long TE (2019) Polymer Design for 3D Printing Elastomers: Recent Advances in Structure, Properties, and Printing. Prog Polym Sci:101144. doi:https://doi.org/10.1016/j.progpolymsci.2019.101144

45. Liu C-S, Lin L-Y, Chen M-C, Horng H-C (2017) A New Performance Indicator of Material Flow for Production Systems. Procedia Manufacturing 11:1774–1781. doi:https://doi.org/10.1016/j.promfg.2017.07.311

46. Soltesz J, Rutkofsky M, Kerr K, Annunziata M (2016) The workforce of the future: Advanced manufacturing's impact on the global economy. http://www.ge.com

47. Gómez-Luna E, Fernando-Navas D, Aponte-Mayor G, Betancourt-Buitrago LA (2014) Literature review methodology for scientific and information management, through its structuring and systematization. Dyna 81(184):158–163. doi:http://dx.doi.org/10.15446/dyna.v81n184.37066

48. Kavanagh MJ, Johnson RD (2017) Human resource information systems: Basics, applications, and future directions. Human Resources, 4 edn. Sage Publications, Thousand Oaks, CA, U.S.A

49. Gatewood R, Feild H, Barrick M (2015) Human resource selection: Nelson Education. Human Resources, 7 edn. Cengage Learning, Mason

50. Institute MG (2018) Demand for these skills will rise dramatically by 2030. Mansueto Ventures, New York

51. MarketWatch I (2020) Top trends of Additive Manufacturing market 2020, statistical analysis, growth and forecast to 2023. MarketWatch. https://www.marketwatch.com/press-release/top-trends-of-additive-manufacturing-market-2020-statistical-analysis-growth-and-forecast-to-2023-2020-01-02. Accessed 2020.01.15 2020

52. Gautam R, Idapalapati S, Feih S (2018) Printing and characterisation of Kagome lattice structures by fused deposition modelling. Materials Design 137:266–275. doi:https://doi.org/10.1016/j.matdes.2017.10.022

53. Savini A, Savini GG (2015) A short history of 3D printing, a technological revolution just started. In: ICOHTEC/IEEE (ed) International History of High-Technologies and their Socio-Cultural Contexts Conference (HISTELCON), Tel-Aviv, Israel, 18–19 Aug. 2015 2015. Institute of Electrical and Electronics Engineers (IEEE), Tel-Aviv, Israel, p 118. doi:https://doi.org/10.1109/HISTELCON.2015.7307314

54. Hanson M (2020) The best 3D printers in 2020. Digital Camera World. https://www.digitalcameraworld.com/buying-guides/best-3d-printer. Accessed 01.24.2020 2020

55. Technologies V (2020) FDM and FFF materials. Vexma Technologies. https://vexmatech.com/about-us.html. Accessed 02.02.2020 2020

56. Coporation DSS (2017) SOLIDWORKS. 2017 SP2 edn., Waltham,MA, U.S.A

57. Austodesk (1982) AutoCad. 2020 edn., San Rafael, CA, U.S.A

58. Co. H-WG (2018) Repetier. 2.0.5 edn. Willich, Germany

59. B.V. U (2018) Ultimaker Cura Software. 4.1 edn., Geldermalsen, Netherlands

60. Industries M (2009) MakerBot. 2020 edn., New York, U.S.A

Figures
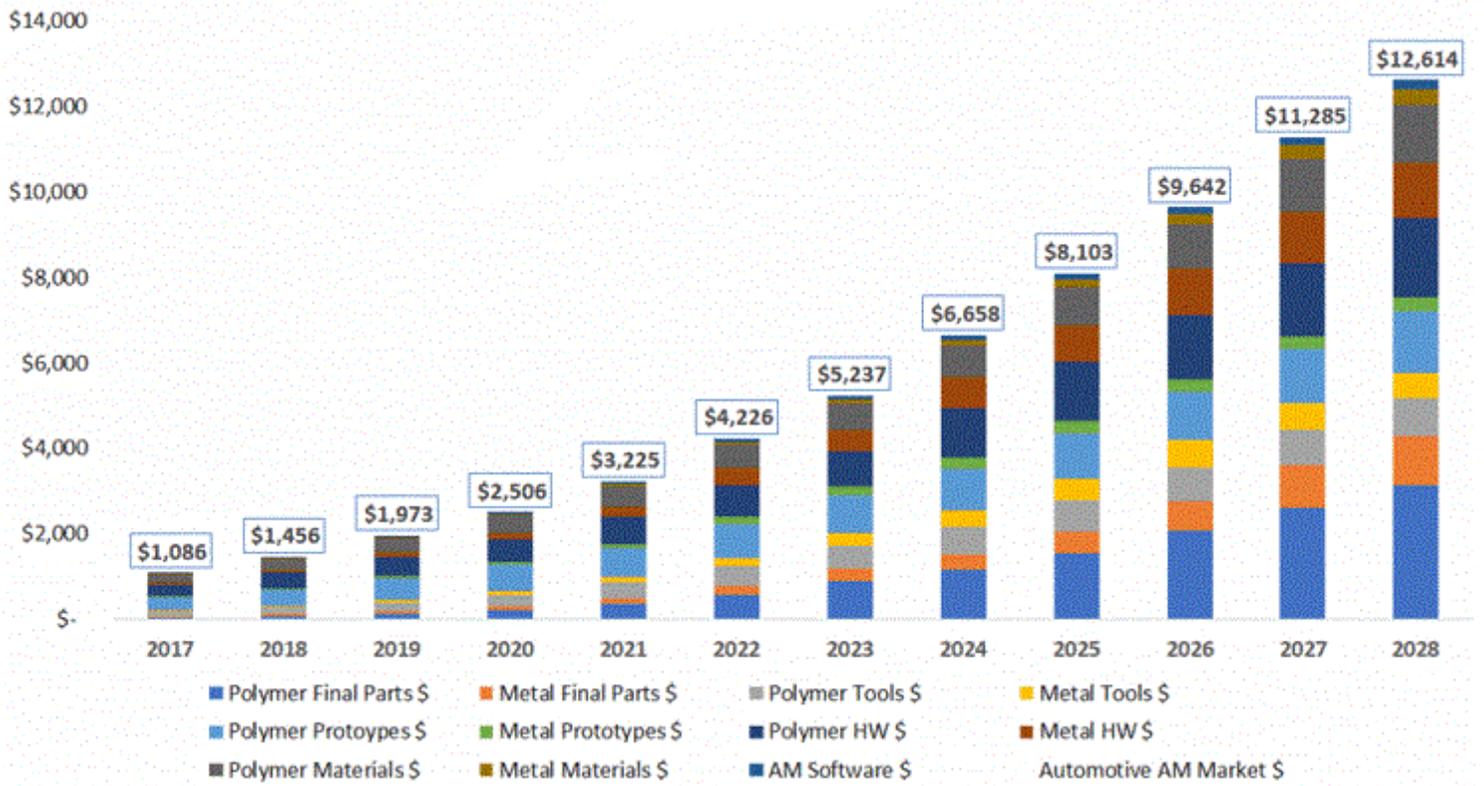
Figure 1

Forecast for additive manufacturing in the automotive industry. Source SmartTech (2019)
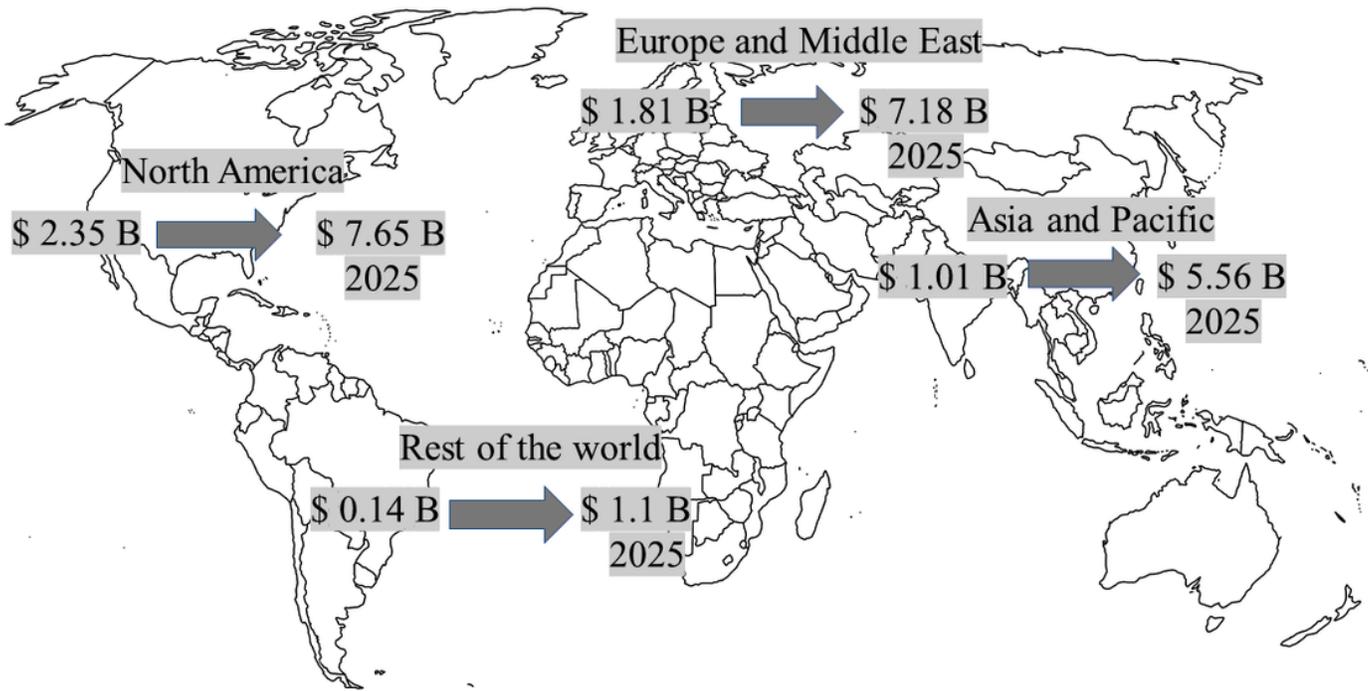
Figure 2

Market forecast for Additive Manufacturing [20]. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
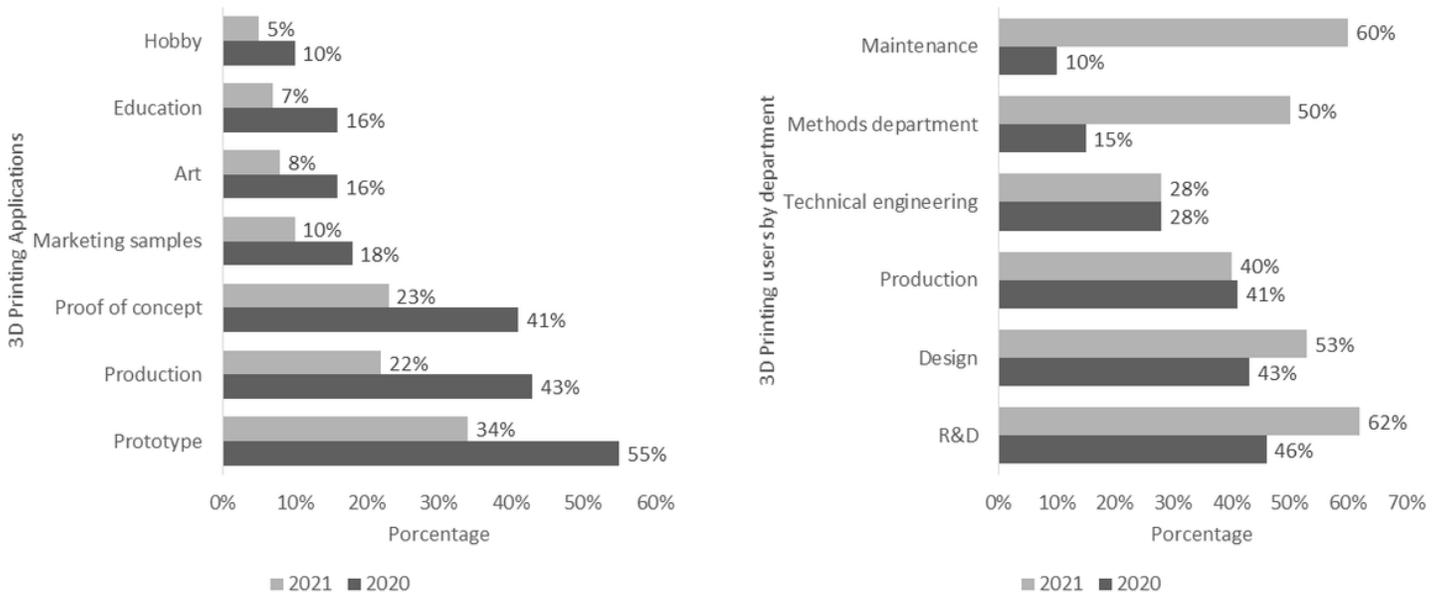
Figure 3

Development trend for the Fused Filament Fabrication technology for 2020-2021
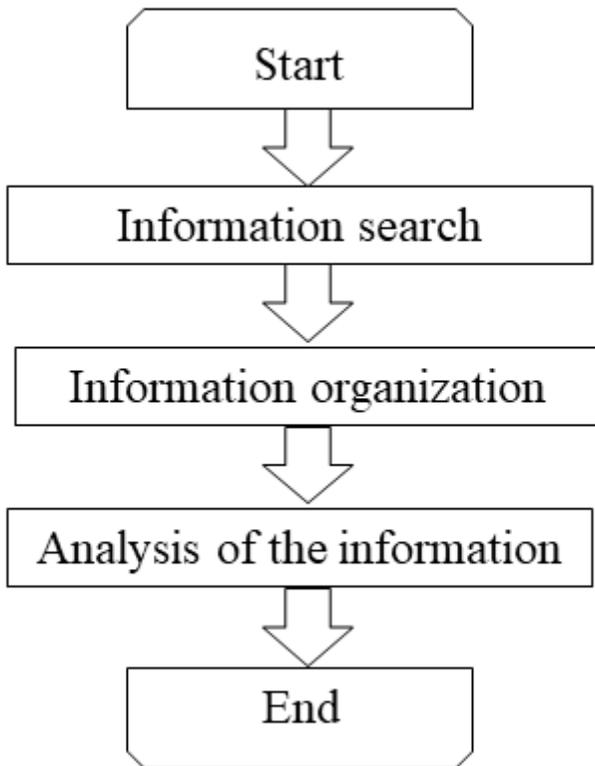
Figure 4

Methodology used for the search, organization, and analysis of the information

$$Yt = 24.7 - 15.04*t + 1.927*t**2$$
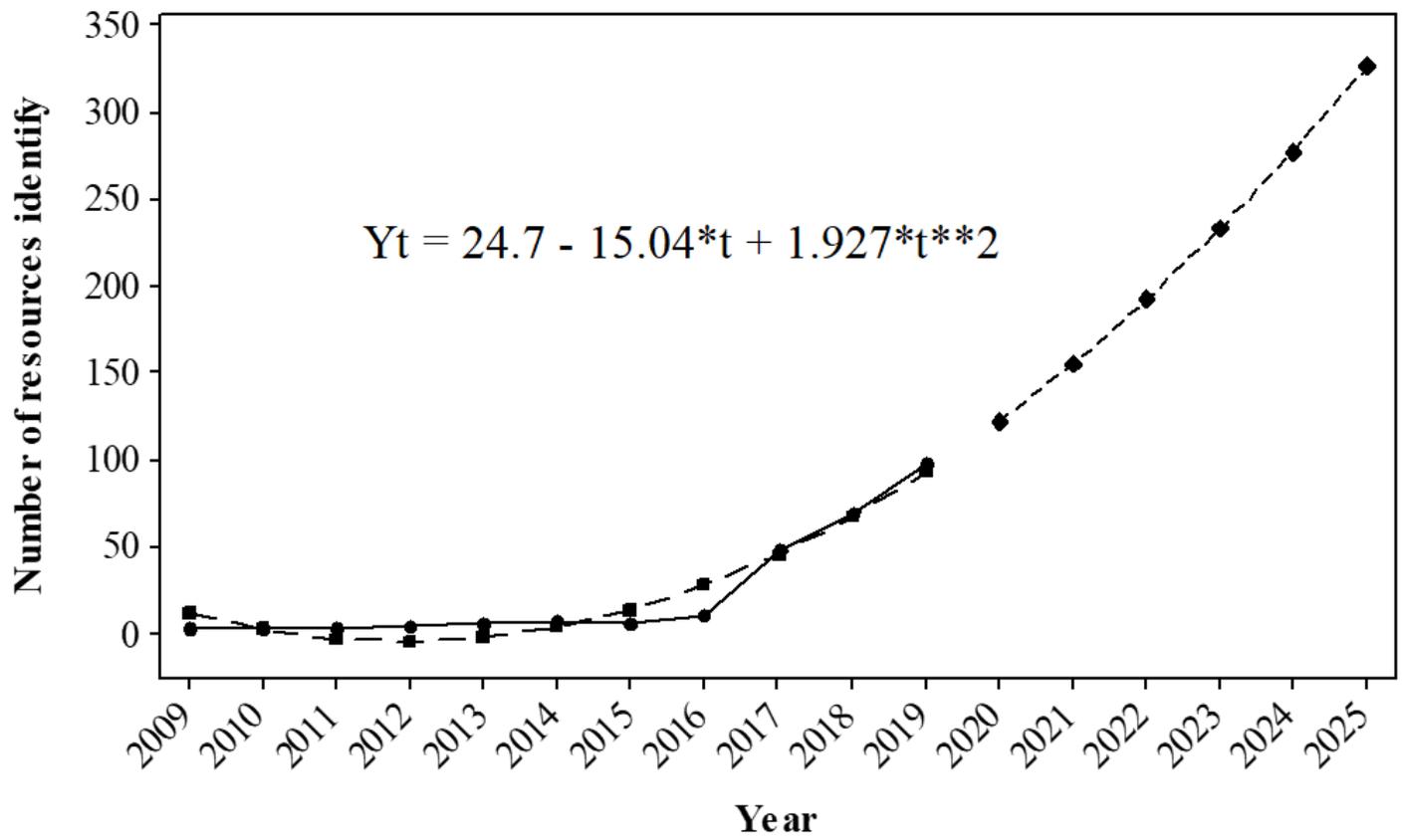
Figure 5

Search syntax matching trends between combinations of "Fused Deposition Modeling", "Fused Filament Fabrication" and "Manpower" terms

$$Yt = 185.4 - 165.7*t + 33.28*t**2$$
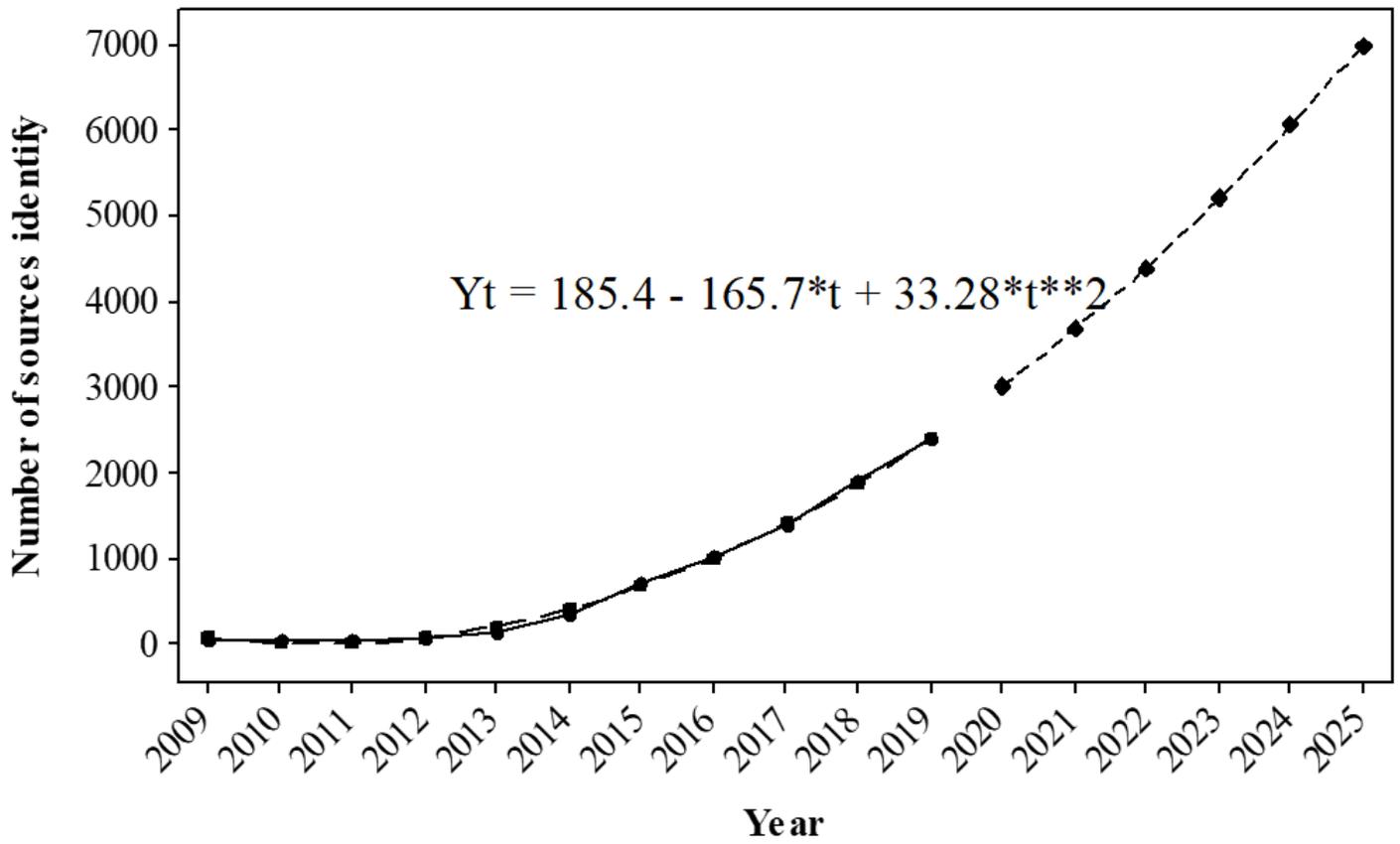
Figure 6

Search syntax matching trends between combinations of the "Fused Deposition Modeling", "Fused Filament Fabrication" and "machinery" terms

$$Yt = 451.5 - 206.6*t + 27.08*t**2$$
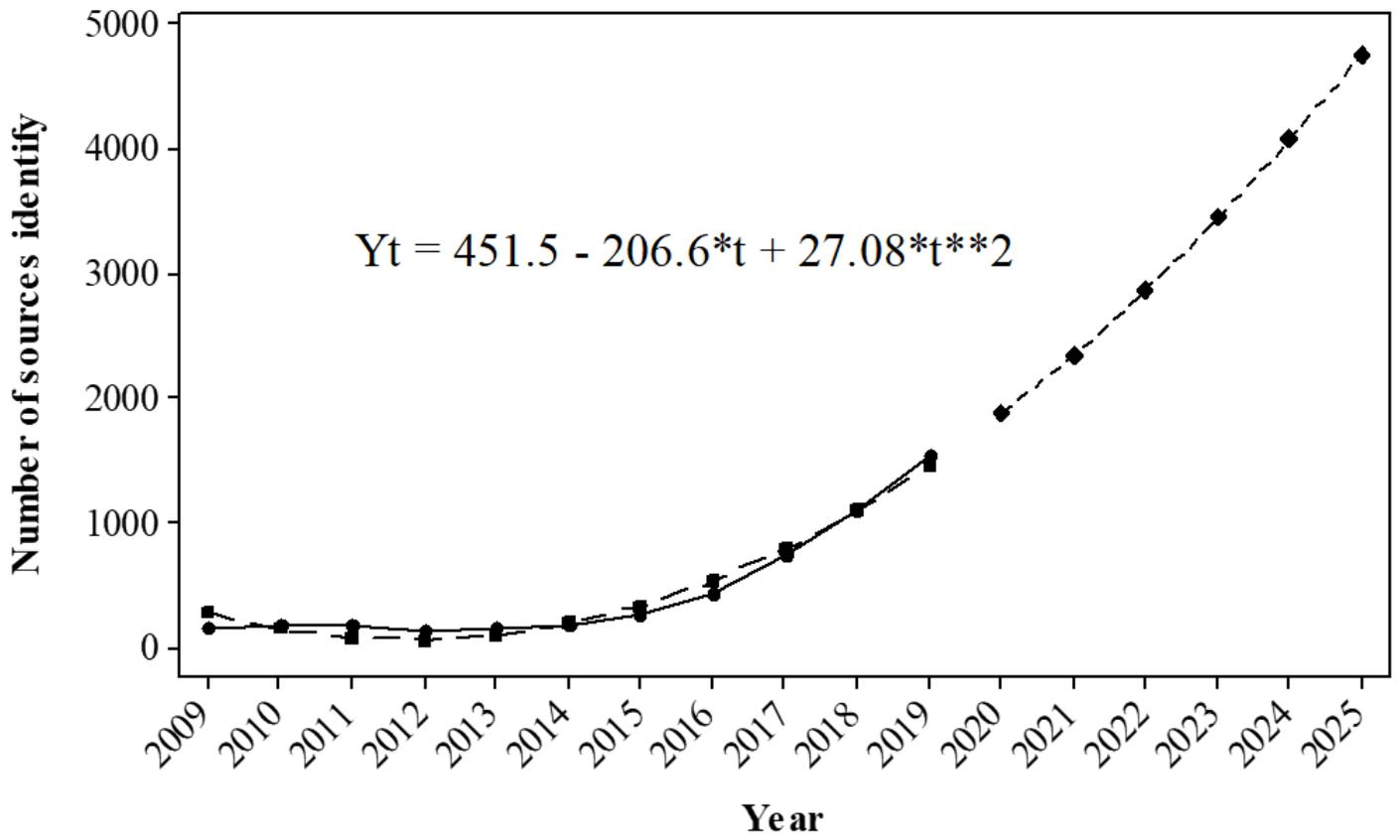
Figure 7

Search syntax matching trends between combinations of the "Fused Deposition materials", "Fused Filament Fabrication" and "materials" terms

$$Yt = 210.3 - 106.8*t + 16.72*t**2$$
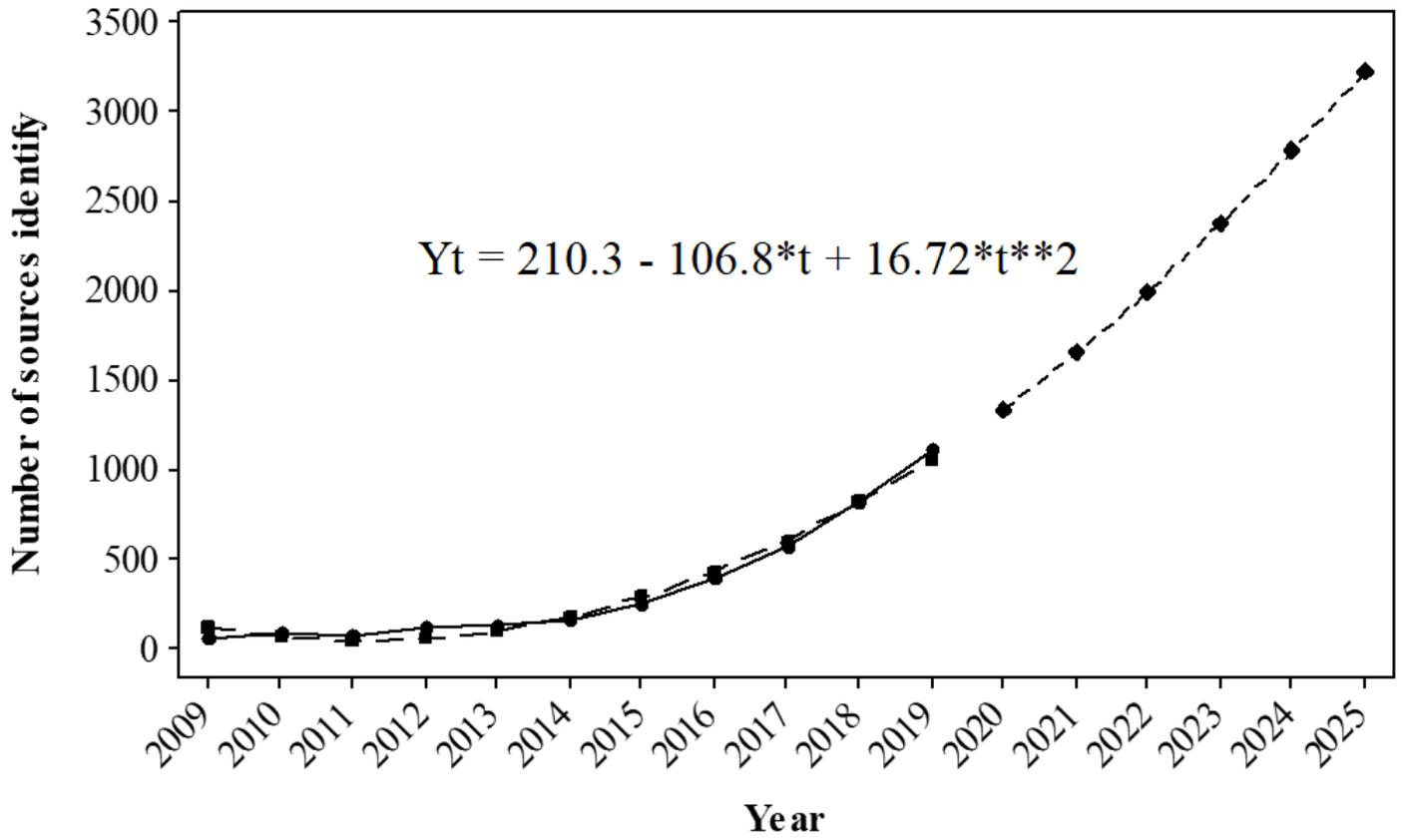
Figure 8

Search syntax matching trends between combinations of the "Fused Deposition", "Fused Filament Fabrication" and "methods" terms
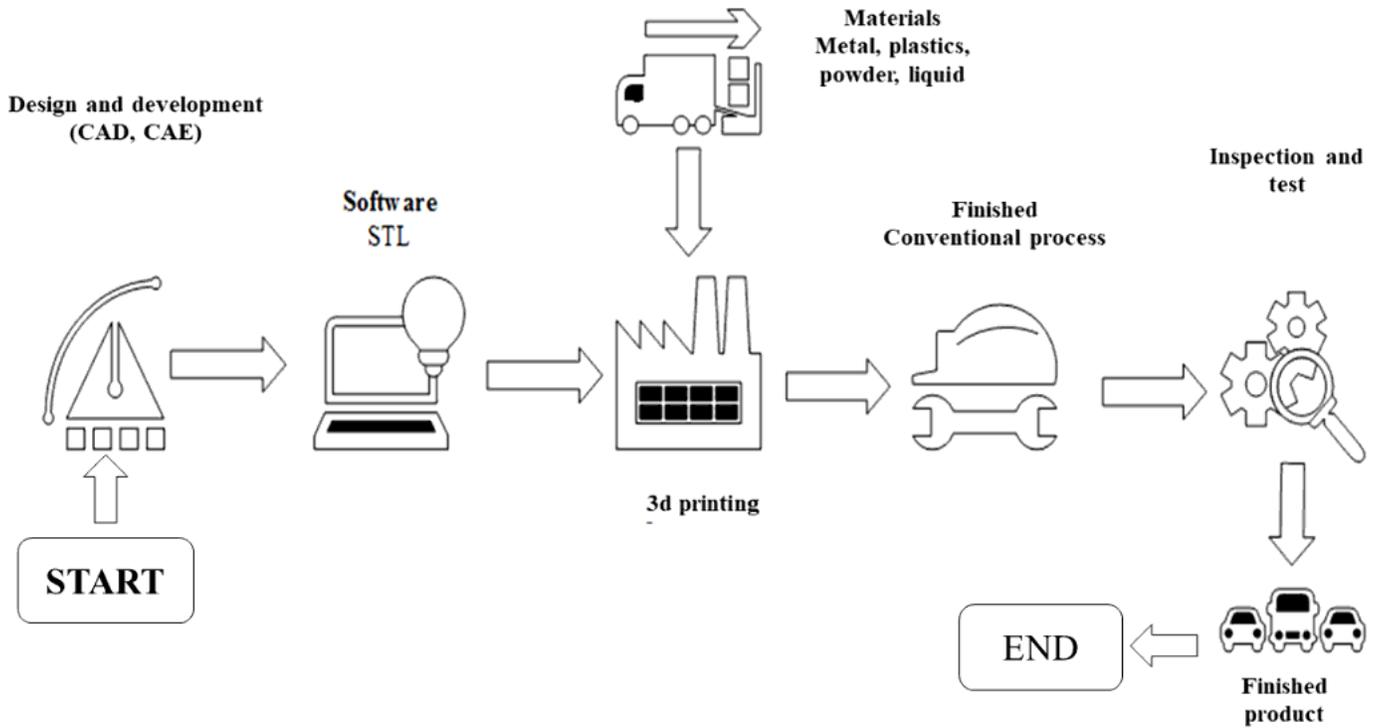
Figure 9

Method used for the component printing through the FFF technology


$$Yt = 44.7 - 26.13*t + 4.061*t**2$$
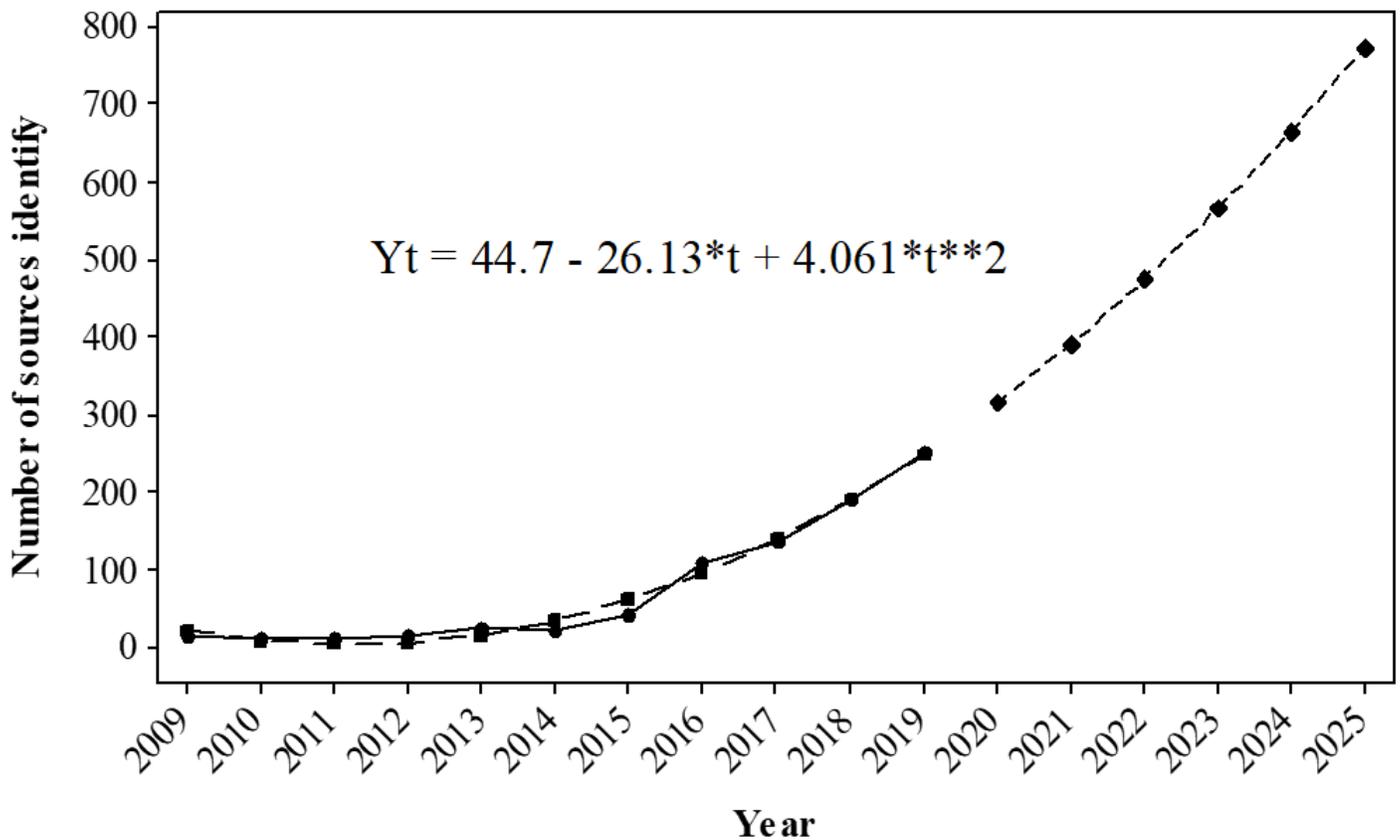
Figure 10

Search syntax matching trends between combinations of the "Fused Deposition", "Fused Filament Fabrication" and "management" terms