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ANALYSIS OF TECHNOLOGICAL MATURITY OF ADDITIVE MANUFACTURING BASED ON S-CURVE
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Abstract. *Additive Manufacturing (AM) is one of INDUSTRY 4.0 technologies that has been expanding its applications and uses in industrial sector, year after year. Technologies such as FDM (Fused Deposition Modeling); SLA (Stereolithography Apparatus); SLS (Selective Laser Sintering), as well as the most recent ones such as MJF (Multi Jet Fusion) stand out as most used. This dissemination of AM is directly related to characteristics inherent to 3D printing, such as: flexibility for mass customization, redesign of supply chains and production capacity of parts with complex geometries in addition to the great potential to improve mechanical resistance/weight ratio. However, there are still several challenges that need to be overcome for consolidation of AM as a widely used process, such as the gap itself in understanding possibilities and benefits arising from the application of AM, as well as its application in final products and not only for prototyping. In this study, AM technologies were analyzed in terms of their life cycles based on patent data sets associated with the S-curve concept, along with expert assessment. For that, it was used models by time series and growth curves for mathematical identification of the maturity of analyzed technologies. From the process point of view, it was found that AM is a technology that has not yet reached maturity. Regarding specific processes, the MJF has great potential to serve industrial applications that permeate from the health industry to the automotive sector, including consumer goods, oil and gas and others. In line with these technological trends, AM bureaus have been implemented in several countries around the world, collaborating with the dissemination of this technology in the market. In this context, the implementation of an AM Bureau at SENAI CIMATEC PARK (Bahia, Brazil) emerges as an important action to support Brazilian industry in industrial production, transition to INDUSTRY 4.0, in addition to developments related to AM.*
Keywords: *Additive manufacturing, S-curve, Industry 4.0, Multi Jet Fusion, Additive manufacturing service bureau.*

1. INTRODUCTION

The great competitiveness of markets with the diversification of competition, means that new products are launched in less time and, if possible, customized. However, each new product requires investments for its creation, ranging from market studies and identification of demand to its withdrawal from the market. In this way, the development of new design and production technologies for consumer goods takes place, aiming to meet the demands of consumers. In this context of competitiveness and efficiency, new concepts such as Industry 4.0 emerge.

Industry 4.0, or Fourth Industrial Revolution, encompasses technologies for automation, data exchange and uses of cyber-physical systems, internet of things, cloud computing, digital twin and artificial intelligence technologies. The focus of the Fourth Industrial Revolution is on improving the efficiency and productivity of processes coupled with mass customization. Industry 4.0 seeks to implement "Smart Factories" and modular and flexible structures. Cyber-physical systems monitor physical processes, create a virtual copy of the physical world, and make decentralized decisions. With the internet of things, cyber-physical systems communicate and cooperate with each other, and with humans, in real time and, through cloud computing, both internal and intra-organizational services are offered and used by value chain participants. However, to reach the speed required by the market, there is a need to use disruptive production technologies, such as Additive Manufacturing [1].

Conventional manufacturing processes are generally not economically and temporally competitive for reduced or customized batch demands. Thus, to fill this gap, rapid prototyping technologies emerged and one of the subsets is Additive Manufacturing (AM). AM or 3D printing refers to a set of manufacturing technologies able to quickly building three-dimensional objects by successively adding thin layers. Although AM was first developed in the 1980s, the technology is still primarily applied to prototyping and rapid tooling [2]. The printing process is not fully understood and controlled to be used reliably in printing structural parts. Due to the complex geometry and layer-by-layer printing process, printed parts can present distortions, residual stresses, delamination and defects that make them unusable in some applications. Finite element simulations of the AM process can be highly effective in understanding the cause of these defects and predicting then in-service performance of printed parts. However, most finite element codes are not designed to simulate AM processes. Due to the large amount of material which is progressively deposited on the part, under which the thermal sources constantly move, making heat transfer a complex problem, combined with this progressive addition of material, there is a difficult multi-physical problem to solve. Adding to the complexity of the technology, the specificities existing in each AM process and in each material must be considered.

AM has a series of different processes that are categorized into seven main technology classifications that use as a basis for definition the type of bond between the materials, the shape of the material that is deposited in the system (liquid, particulate, laminate, filament), the deposition and union operations of the process and the source and type of applied energy applied. These groups of technologies are defined as Binder jetting, Direct energy deposition, Material extrusion, Material jetting, Powder bed fusion (PBF), Sheet lamination and Vat photopolymerization [3].

Among these, one that stands out the most is the Powder bed fusion technology that is defined as a process in which thermal energy selectively fuses regions of a powder bed, a region which feedstock is deposited and selectively fused by a heat source or bonded by means of an adhesive to build up parts from 3D models [3]. Some of the main advantages of the Powder bed fusion processes are the high resolution and high print quality, which make it suitable for printing complex structures used in various industries for advanced applications such as scaffolds for tissue engineering, lattices structures, aerospace and electronics [4]. In the category of Powder bed fusion technologies there are several AM processes that enable the processing of a wide range of materials, which can be composites, ceramics, polymers (for example, PP (Polypropylene), PA (Polyamide), PC (Polycarbonate), TPU (Thermoplastic Polyurethane)) and metals (for example, Titanium, Aluminum and Stainless Steel). These technologies are Multi Jet Fusion (MJF), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), Direct Metal Laser Melting (DMLM) and Electron Beam Melting (EBM), in addition to others still under development [5].

There is still great interest in developing Powder bed fusion technologies or improving the existing ones. The biggest trends regarding this technology are the production of lightweight parts with good strength, production with high performance alloys, development for composite materials, establishing new methodologies of quality control and reliability, developing different component postprocessing, integrating of additively manufactured components into existing systems, developing new approaches to life cycle analysis and new ways of cost and resource management [6].

In this context, powder materials have great advantages because of the high utilization rate, wide variety of materials and easy manufacturing process. Meanwhile, excess powder is removed at the end of the manufacturing cycle and can be reused in the next printing process. The polymeric powders can act as a support for the part, allowing for greater design freedom, which is a big challenge for other 3D printing technologies [7].

In relation to new family technologies of Powder bed fusion, a highlight is given to the MJF which is a 3D printing technology developed by the HP company that uses powder as a raw material. MJF is one of the newest technologies in this landscape, started rolling out in 2016 and is designed to deliver new levels of part quality quickly and cost-effectively compared to the existing 3D printing technologies. The printed piece quality is determined by the interaction of the printing device and the materials used for printing. Studies comparing AM processes have shown that MJF has some advantages in dimensional accuracy, surface roughness and printing speed, which has a great potential to significantly increase efficiency for industries [8].

At the market level, an important study which demonstrates current level of application of AM technologies in market is the Gartner Hype Cycle [7]. It provides insight into how these technologies are being applied over time, providing solid comprehensions to manage these technologies within companies' business objectives.

The Gartner Hype Cycle graph referring to application of AM technologies (3D Printing) is shown in Figure 1. The use of this technology for Service Bureaus (“3D Printing Service Bureaus”) is positioned in "Plateau of Productivity" (which corresponds to the phase where conventional adoption begins to expand, in that the benefits are clearly defined). This means that the adoption of AM for use in the Service Bureau starts to become relevant in the market and with applicability proven and validated by companies and institutions.

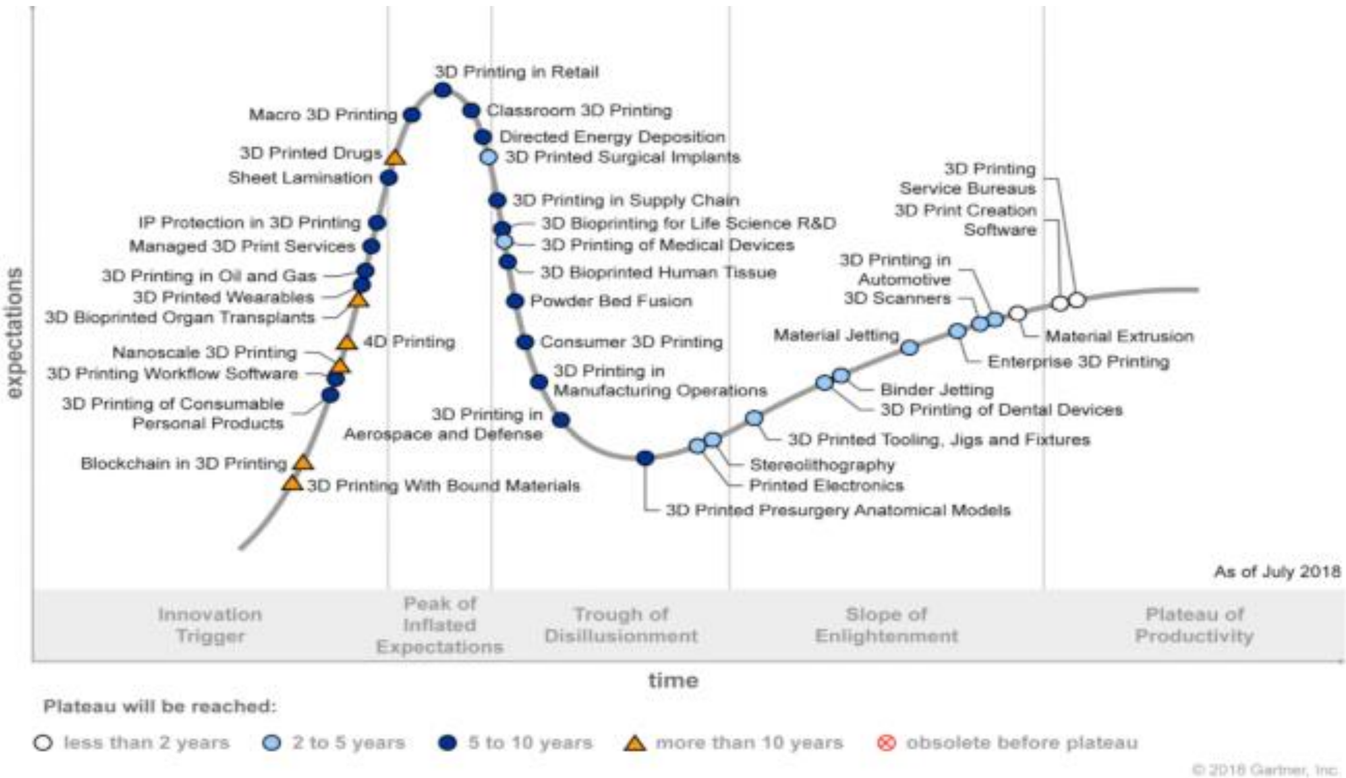

Figure 1. Gartner Hype Cycle graph to application of Additive Manufacturing technologies [9].

For perfoming AM services, 3D Printing Service Bureaus are fundamental, as they facilitate the adoption and implementation of 3D printing in many industries, allowing companies to access this technology (without requiring high initial investment in CAPEX). A mapping carried out by the senior editor of the AM website (Stephanie Hendrixson), shows more than 200 (two hundred) AM Services Bureaus in the United States alone [10].

In Brazil, there are some 3D Printing Service Bureaus that mainly use FDM, SLS and SLA as technologies. Some of these Bureaus are: Usintek, Inkubetech, Fasparts, Prototype Factory, 3DEdge, among others. Assessing trends in Manufacturing Services Bureaus, the AMFG report [11] presents important information regarding the Bureau's business around the world. Providing AM services with polymer parts remained the main service in 2019. However, 3D metal printing is on a high growth trend, expected to generate $6.7 billion in revenue by 2023 according to SmarTech Analysis (apud AMFG, 2019).

The 3DPBM report [12] shows the revenues of the largest companies in the 3D printing sector in the world. This report includes 3D printer manufacturers, service providers and material manufacturers. Among the service providers (Bureaus), the top five stand out: Materialise (US$ 173 million), Protolabs (US$ 61 million), Shapeways (US$ 60 million), ToolCraft (US$ 50,2 million) and Jabil (US$ 50 million).

In 2019, the AM sector grew 21.2% worldwide, reaching a transaction value of 12 billion dollars (considering sales of hardware, software, inputs and services). In 2020, even with the pandemic, growth was 7.5%, reaching a turnover of approximately 12.9 billion dollars [13]. For 2021, the trend is to continue growing at a rate between 20-25%, with variations resulting from the pandemic (decrease/advance).

Aiming to assess the AM technologies, one of the ways to analyze is through the technology life cycle analysis. In recent studies, Oliveira *et al.* [14] brought that the technology life cycle analysis (TLC) can be applied to different technologies, and can be analyzed from some aspects, such as embryonic, growth, maturity and aging. Using this analysis together with the S-curve model generated from the study of patents, it is possible to evaluate the additive manufacturing technology maturity, which supports the understanding of the evolution in this technology and guides for the sustainable development of the AM process. The model used in this research was proposed in the article by Oliveira et al., [14] with the objective of evaluating technological changes and bringing adaptations for the planning of R&D resources.

The TLC concept shown in Gao *et al.*, [15] demonstrates this technology in two fields, the technological impact and integration of product or process, in which they are separated into four stages: emerging, growth, maturity and saturation. Madvar et al. [16] shows that the patents study is used to obtain information from a particular technology or industry, since the number of patents follows a trend similar to the S-curve pattern, at the beginning of the technology with few patents published, then a rapid growth until its stabilization.

Thus, the objective of this study is to verify the maturity level of the AM technologies and more specifically those that work with Powder Bed Fusion through the search for patents on the Derwent Innovation platform and scientific articles on the ScienceDirect website and compare with the technology results of Multi Jet Fusion, which is the central focus of this article.

2. METHODOLOGY

2.1. PATENT SEARCH

The database for the analysis of the theme proposed in this work was obtained through a systematic survey of patent data through different patent databases. The *Derwent Innovation* platform (www.derwentinnovation.com) was used to search in several patent banks, with the search configured to identify key words only in abstracts, in the database of all authorities. Only INPADOC (International Patent Documentation) families were selected, to disregard equal patents present in the database of different authorities.

Three different search strategies were applied to this research, defined by the terms used in the Derwent platform. The Figure 2 shows a systemic visualization of these strategies, while Table 1 presents the terms applied in each search strategy. The first strategy focused on mapping all patents that address the terms "Additive manufacturing" or "3D printing", considering all possible technologies. The second strategy aimed to specify the research filtering from the first strategy, only those that address the terms referring to all printing technologies classified as Powder Bed Fusion. The third and final search strategy aimed to further specify the search, focusing specifically on Multi Jet Fusion technology from the first strategy. The choice of these three search strategies was intended to first understand the general context of the maturity of all AM technologies, and then narrow down to understand the maturity of the Powder Bed Fusion processes, and then further deepen the understanding for the Multi Jet Fusion technology, as the central focus of this work. The choice of these search strategies is based on two requirements: I) Having coherent results that are part of the same group so that they can be properly compared, and II) Filtering the results so that all applied terms are consistent with the main theme, that is, exclude all patents that do not address additive manufacturing or 3D printing.

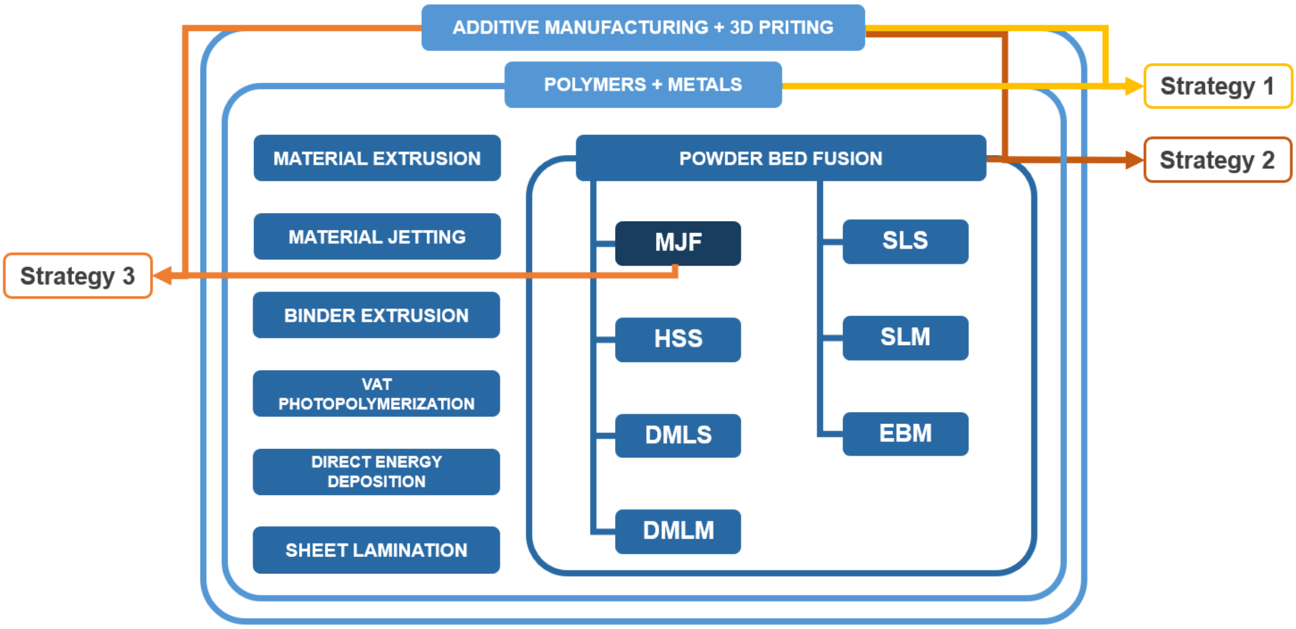

Figure 2. Schematic diagram of the search strategies applied in this research.

Table 1. Terms applied in each search strategy.

Strategies	Terms
1° - General AM	AB=(((additive ADJ manufacturing) OR (3d ADJ printing)) AND ((polymer OR plastic OR polymeric OR thermoplastic OR thermoset OR resin OR elastomer OR elastomeric OR rubber OR (Acrylonitrile ADJ butadiene ADJ styrene) OR polyamide OR nylon OR (polylactic ADJ acid) OR polylactide OR PVA OR (Polyvinyl ADJ alcohol) OR polycarbonate OR PP OR polyethylene OR PCL OR Polycaprolactone OR PEEK OR PEAK OR (Polyether ADJ ether ADJ ketone) OR polyaryletherketone OR PLGA OR PLG OR (poly adj lactic-co-glycolic ADJ acid) OR PS OR Polystyrene OR (Thermoplastic ADJ polyurethane) OR TPU OR polyurethane or TPA OR (Polyamide ADJ thermoplastic ADJ elastomer) OR Polyphthalamide) OR (metal OR metalic OR steel OR (stainless ADJ steel) OR (tool ADJ steel) OR (maranging ADJ steel) OR inconel OR aluminum OR titanium OR copper OR bronze OR brass OR gold OR silver OR chrome OR nickel) OR ((powder ADJ bed ADJ fusion) OR (material ADJ extrusion) OR (stereolithography) OR (photopolymerization) OR (material ADJ jetting) OR (binder ADJ jetting) OR (sheet ADJ lamination) OR (direct ADJ energy ADJ deposition)));
2° - Powder bed fusion Technologies	AB=(((additive ADJ manufacturing) OR (3d ADJ printing)) AND ((polymer OR plastic OR polymeric OR thermoplastic OR thermoset OR resin OR elastomer OR elastomeric OR rubber OR (Acrylonitrile ADJ butadiene ADJ styrene) OR polyamide OR nylon OR (polylactic ADJ acid) OR polylactide OR PVA OR (Polyvinyl ADJ alcohol) OR polycarbonate OR PP OR polyethylene OR PCL OR Polycaprolactone OR PEEK OR PEAK OR (Polyether ADJ ether ADJ ketone) OR polyaryletherketone OR PLGA OR PLG OR (poly adj lactic-co-glycolic ADJ acid) OR PS OR Polystyrene OR (Thermoplastic ADJ polyurethane) OR TPU OR polyurethane or TPA OR (Polyamide ADJ thermoplastic ADJ elastomer) OR Polyphthalamide) OR (metal OR metalic OR steel OR (stainless ADJ steel) OR (tool ADJ steel) OR (maranging ADJ steel) OR inconel OR aluminum OR titanium OR copper OR bronze OR brass OR gold OR silver OR chrome OR nickel)) AND (((powder ADJ bed ADJ fusion) OR (powder ADJ bed)) OR (MJF OR (multi ADJ jet ADJ fusion)) OR (HSS OR (high ADJ speed ADJ sintering)) OR (SLS OR (selective ADJ laser ADJ sintering)) OR (SLM OR (selective ADJ laser ADJ melting)) OR (DMLS OR (direct ADJ metal ADJ laser ADJ sintering)) OR (DMLM OR (direct ADJ metal ADJ laser ADJ melting)) OR (EBM OR (electron ADJ beam ADJ melting)))));
3° - Multi Jet Fusion	AB=((((additive ADJ manufacturing) OR (3d ADJ printing)) AND (MJF OR (multi ADJ jet ADJ fusion))));

It is also important to consider that this survey is restricted to sampling and that does not verify patent documents that are in secrecy or inactive. The search was carried out between 1st and 2nd July 2021 and the results include only the active patents deposited until this period.

2.2. PUBLICATIONS SEARCH

To analyze the trends in the amount of publications for AM technologies, the same terms used in patent research were applied (presented in Table 1), making use of the same principles explained in the previous topic. The research aimed to list the number of scientific papers published per year for each search strategy, obtaining data for publications per year and accumulated per year. For this research, the *ScienceDirect* search platform was used, with no specifications for article type, tittle and subject area.

2.3. DATA PREPARATION AND STATISTICAL MODEL

The preparation of the data set was made from the use of the patents and papers accumulated every year according to each set of words used, it was organized with the number of results per year and used the value zero for those which were without reference to the date of deposit, thus following the model of the S-Curve (evaluated by the priority date). For the statistical models used in this research, they were developed and applied in the R Studio environment [17], the models used were described in the studies of Oliveira *et al.*, [14], in which the time-series and the growth-curves models serving for growth analysis and visualize technological trends.

3. RESULTS

From data analysis through the S curves methodology, exponential smoothing approach presented the best fit, for both patent and publication data in the contexts of powder bed fusion technologies and AM in general, as shown in Figure 3 and Figure 4. In the same way, Figure 5 shows the data for the publication search. Although it is not possible to represent an s-curve, the smoothing on an exponential curve possibly indicates that the technology is in the growth stage, which is characterized by high year-over-year variation [18], and the existence of pace technologies with high competitive impact that have not fully integrated into new products or processes [15]. An additional attempt was made to use the 2nd best fit, but there was a covariance error in the analysis. This fact also reinforces the possible state of technology. The amount of data on the Multi Jet Fusion process, both for patents and for publications, was too low for the statistical analysis to be carried out. It is possible to associate that this particular technology would be in an equally embryonic state of maturity.

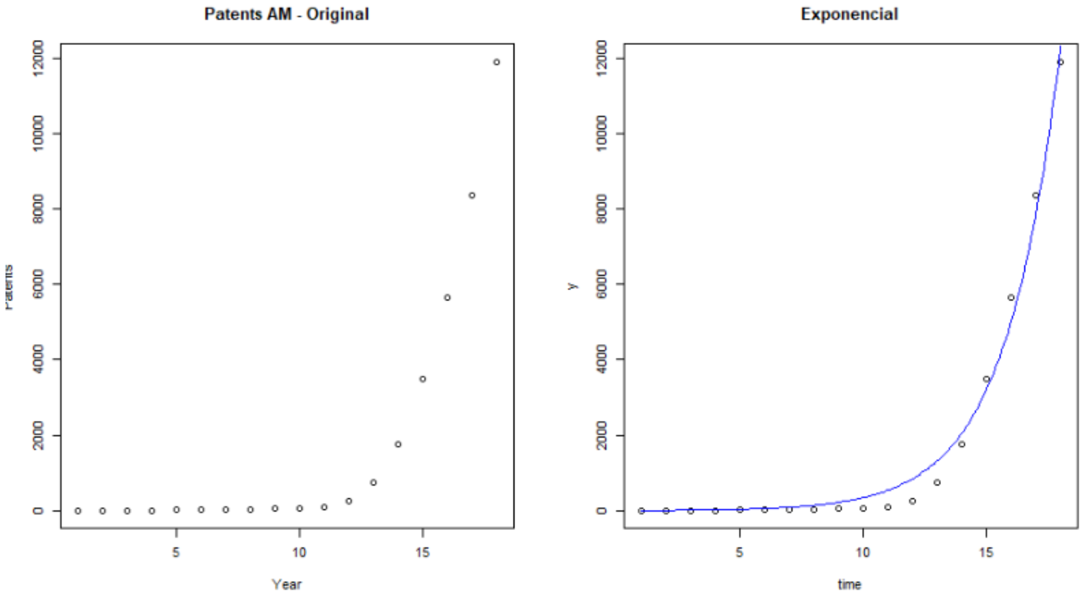

Figure 3. Graphs of additive manufacturing patent data analysis.

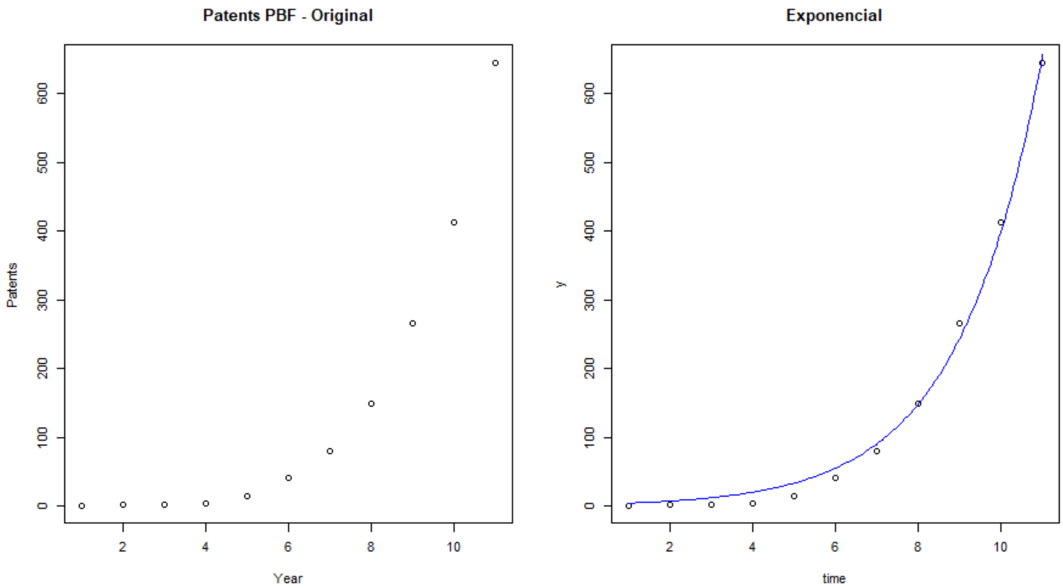

Figure 4. Graphs of powder bed fusion technologies patent data analysis.

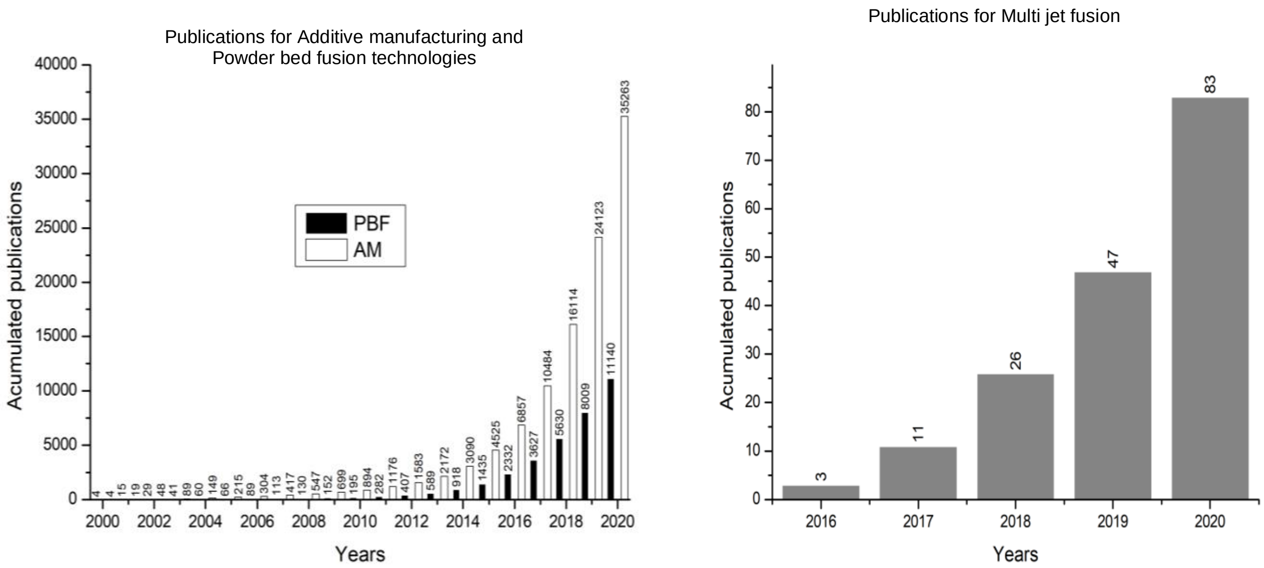

Figure 5. Graphs of publications for all three research strategies.

A similar behavior was also found in the study by Nicolás *et al.* [19] for some AM categories, who performed a technology maturity study based on S-curves to determine the technology readiness level (TRL) of the different categories of AM. In their work, they identified that the Binder jetting and Sheet lamination technologies are in TRL 1-2 and Direct energy deposition is classified as TRL 4-5. The categories of Powder bed fusion, Material extrusion, Material jetting and Vat photopolymerization are classified as TRL 6-7, according to the TRL indicator, the most accepted approach for assessing technological maturity on a standardized numerical scale, developed by the US National Aeronautics and Space Administration (NASA) [19].

Although the data reveals a state of early maturity, the sudden growth in development and research reflects the heightened interest in these technologies. The AM has been a reference over the last decade as a significant stepping stone in the global shift toward mass customization, as a technology that will cause major impacts on supply chains, applying on-demand product markets, significantly reducing logistics and energy costs. As one of the main enabling and disruptive technologies in the industry 4.0, AM will transform the business models of different industries, replacing or supporting others manufacturing processes and leading the subsequent main industrial revolution [19], [20]. The main trends regarding the advancement of AM maturity is that it will become a cheaper and faster technology that can be applied to mass production, as well as the development of new materials for AM and the expansion of markets [20].

Among the AM categories that demonstrate greater maturity, Powder bed fusion processes stand out for their better printing resolution, greater freedom of complexity and greater application feasibility, being eligible to process polymers, metals, ceramics and composites [5]. Especially in the polymer AM market, this category has the highest growth projection and is expected to be the main player in this sector [21]. Among the polymer Powder bed fusion technologies, MJF stands out due to the better mechanical performance of printed parts, lower incidence of defects, faster printing time, better print quality, more energy efficiency, lower production cost and higher market growth rate among the competing polymer Powder bed fusion technologies [22]–[24]. The Wohlers Report 2020 shows that the majority of respondents which are expanding AM capability would choose HP's MJF technology and EOS' polymer and metal PBF technology, thus showing increasing interest in the PBF family of technologies [25].

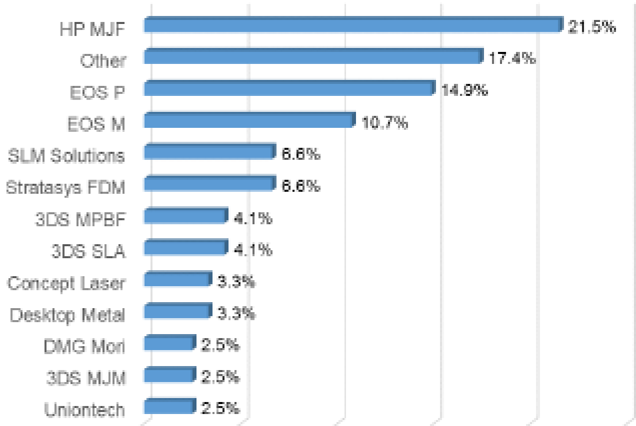

Figure 6. Main technologies chosen by respondents to expand AM capability. (Wohlers Associates Report 2020) [26].

In this context, it is important to emphasize the role of bureau services in the face of the growth of the AM and 3D printing market, as well as the evolution of the maturity of these technologies. Recent research reveals that service bureaus represent a big part of the AM market. Service providers make up 34% of the global AM landscape, and this percentage must grow [27]. As the technology continues to mature and the industry continues to grow, service bureaus will be able to innovate product development and production by providing valuable specialisms across a range of 3D printing technologies and ancillary services like production on demand, post-processing, 3D modelling and 3D scanning [27]. Given these factors, it is evident that the development of service bureaus for AM is necessary not only to make the advanced and enabling technologies more present in the industry, such as MJF, but mainly to assist in the development of their maturities.

Thus, the implementation of a 3D Printing Service Bureau at SENAI CIMATEC PARK (Bahia, Brazil) with MJF technology, emerges as an important action to support Brazilian industry in industrial production, transition to Industry 4.0, in addition to developments related to AM.

4. CONCLUSIONS

In this study, systematic research was carried out on a *Derwent Innovation* patent platform and a *ScienceDirect* website to verify whether AM technologies are still under development or whether they have already reached stagnation. The main conclusions are:

- For the additive manufacturing in general and powder bed fusion technologies patents, the results showed that the technologies are in full expansion.
- For article data, there is a strong indication that the technology is still in its growth stage of technological maturity since there was no way to represent the S-Curve in these data.
- The amount of data on the MJF process, both for patents and for publications, was too low for statistical analysis to be carried out showing that the technology is also in its embryonic stage.

These conclusions reinforce the fact that AM technologies still deserve interest on the part of researchers in the development of articles and on the part of companies in the creation of patents. It is also important to emphasize that the technologies that are driving developments the most are those that work with powder bed, because as shown, they generate better mechanical performance of printed parts, lower incidence of defects, shorter printing time, better print quality, greater energy efficiency and lower production cost compared to other AM technologies.

5. ACKNOWLEDGMENT

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