Additive Manufacturing and Computational Simulation: A Review of Integrated Technologies and Applications

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ABSTRACT

Additive manufacturing (AM), or 3D printing, is a manufacturing process based on building objects layer by layer from a 3D digital model. This process allows the creation of complex and customized parts with precision and cost reduction. When combined with computational simulation, a technique that enables the creation of virtual models of physical systems or processes, it is possible to validate prototypes before production and optimize product performance, accelerating the development of new components and improving production efficiency. This article presents a literature review of technologies according to ASTM/ISO 52900 standards to disseminate knowledge about AM and its joint use with computational simulation for sustainable development. The main features and applications are presented, as well as the capabilities of simulation software. The study identified which AM techniques are trends in industrial applications and how they are being developed, and how, together with the use of simulation programs, they can bring benefits to the development of sustainable mobility due to the optimization of the use of raw materials, energy expenditure, and weight.

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INTRODUCTION

Additive Manufacturing (AM) is a fabrication process that successively adds material in layers based on information obtained directly from a computational geometric representation [1]. AM creates complex shapes that would be difficult or impossible to produce through conventional techniques. When combined with computational simulation, it is possible to identify and correct issues in the design before the physical production stage. The combination increases process efficiency, ensures final product quality, avoids rework and waste, and optimizes material use. Recent advances in computational simulation for AM technologies also enable virtual testing, saving time and money in product development in this area.

Computational simulation is "the process of creating a computational model of a real system and performing experiments with that model to understand the system's behavior or evaluate possible strategies for its operation [2]. Computational simulation involves creating mathematical and logical models implemented in software, which allows for experiments and data analysis for decision-making. This simulation is a valuable tool for solving problems in complex systems.

Although AM is a technology with the potential to revolutionize the production process, the lack of technical knowledge and qualified professionals, the lack of understanding of possible applications, and high costs due to production failures are some of the reasons that still prevent the implementation of Additive Manufacturing as a traditional fabrication process [1]. Therefore, sharing information on the subject is crucial for understanding the application possibilities of Additive Manufacturing and raising awareness about the benefits and the increase in efficiency by using simulation tools.

Thus, this article aims to conduct a literature review on the leading Additive Manufacturing technologies and the computational simulation tools available in the market to support these production processes.

DEVELOPMENT & DISCUSSIONS

This paper brings a literature review of articles published between 2000 and 2023. The search for articles was done with the following keywords: Additive Manufacturing, Computational Simulation, Design for Additive Manufacturing, Economics of Additive Manufacturing, and the nomenclature of each of the seven

AM processes. After searching on platforms such as Google Scholar, Science Direct, Springer, and MDPI, we found 48 relevant articles (46 international and two national). In addition to the articles, 7 norms were also consulted.

After reading the papers, we compiled the information to present fundamental concepts about AM and the current standards. Then, we identified some trends in the AM field by analyzing the number of published articles. We also addressed other topics, such as design requirements impacting costs and how mechanical properties vary based on the addition principle. Afterward, we discussed the Design for Additive Manufacturing (DfAM) concept to identify at what point in the product development process computational AM simulation can bring benefits. Finally, we discussed the computational simulation capabilities within each addition principle, highlighting how tools can improve the processes.

CURRENT STANDARDS AND AM CONCEPTS – Specific standards are required to meet some technical and regulatory requirements to ensure the quality and safety of products manufactured through Additive Manufacturing processes [3]. These norms also seek to ensure the uniformity and standardization of addition principles, allowing for accurate and comparative assessments of different technologies and materials.

One of the most relevant standards in Additive Manufacturing, ISO/ASTM 52900 [4], establishes terms and definitions for Additive Manufacturing. It standardizes the language used in the field to ensure clear and precise communication among professionals and companies working with AM. ISO/ASTM 52900 defines the general principles and definitions related to Additive Manufacturing, covering the phases from product conception to manufacturing [4]. Its main goal is to provide a foundation for the standardization and development of Additive Manufacturing, allowing the technology to be more quickly and efficiently understood and implemented.

The standard also provides guidelines for the design and manufacture of printed objects, including requirements for materials, manufacturing processes, quality control, and product validation [4]. In addition, it establishes guidelines for documentation and traceability of the entire manufacturing process, helping to ensure the safety and quality of products.

ISO/ASTM 52900 separates Additive Manufacturing technologies into seven categories based on the principles of material addition [4] (Figure 1), which are:

1. Binder Jetting (BJT): "Process in which a liquid bonding agent is selectively deposited to join powder materials" [4].
2. Directed Energy Deposition (DED): "Process in which focused thermal energy is used to fuse materials by melting as they are being deposited" [4].
3. Material Extrusion (MEX): "Process in which material is selectively dispensed through a nozzle or orifice" [4].
4. Material Jetting (MJT): "Process in which droplets of feedstock material are selectively deposited" [4].
5. Powder Bed Fusion (PBF): "Process in which thermal energy selectively fuses regions of a powder bed" [4].
6. Sheet Lamination (SHL): "Process in which sheets of material are bonded to form a part" [4].
7. Vat Photopolymerization (VPP): "Process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization" [4].

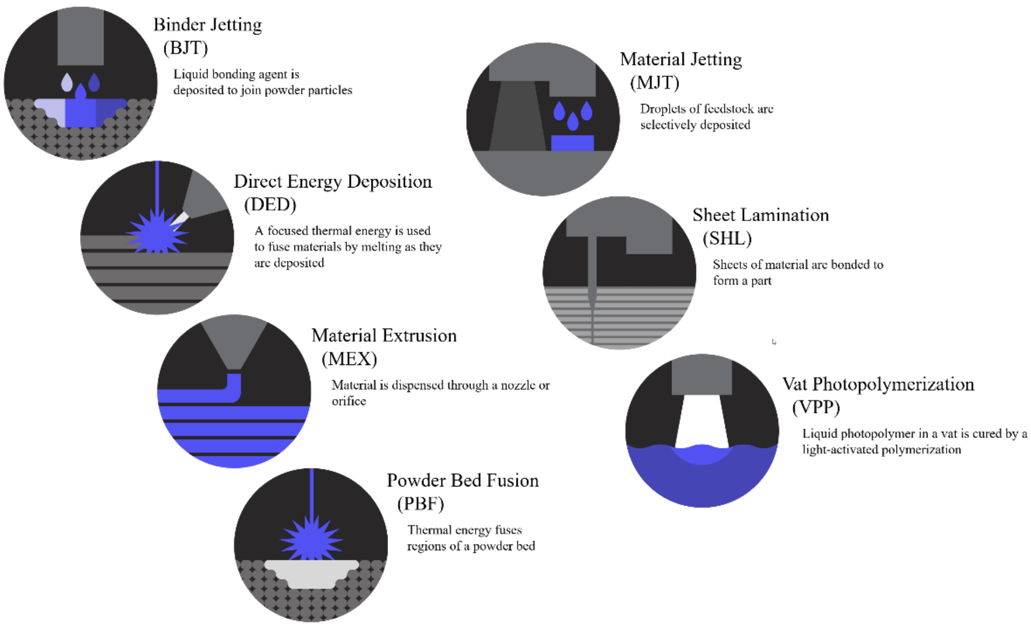

Figure 1. Seven Additive Manufacturing addition principles. Source: adapted from [4, 5]

Although the ISO/ASTM 52900 standard exists and is a reference in the classification of AM technologies, many equipment-producing and developing companies often adopt different names for the developed solutions based on the equipment's operation and the needs addressed. This behavior occurs for various reasons, but mainly due to variations in specific characteristics or to emphasize some critical technology feature [4].

Due to the diversity of terminologies companies use, adopting specific standards and norms for Additive Manufacturing becomes even more essential to ensure the quality, safety, and efficiency of the process and manufactured products. Standardization also facilitates communication among professionals and companies in the sector, promoting the development and dissemination of technology [4]. By applying these standards and compliance with technical and regulatory requirements, Additive Manufacturing can continue to grow and become a viable option for producing a wide range of products [6].

ISO/ASTM 52915 [7] is another significant standard that defines the requirements for preparing AM files and establishes guidelines for creating digital models and print files that ensure accuracy and desired properties in printed objects. There are specific standards for AM in various sectors. AMS-AM-002 [8], for example, is a standard for the aerospace industry and addresses the process requirements to produce metallic powders used as raw material (feedstock) in additive manufacturing of aerospace parts. ISO 13485 [9] establishes requirements for quality management systems in medical devices, while ISO 13485-7 [10] provides guidelines for applying Additive Manufacturing in medical devices. The ISO 12836 [11] standard defines requirements to produce dental products through AM.

AM TRENDS – To analyze trends, we assessed the number of published articles for each category of AM by checking the Scopus database powered by Elsevier. This platform offers access to abstracts, citations, and other information related to scientific articles, books, and conference proceedings in various areas of knowledge. Using specific keywords, we quantified the publications and compared each technology to identify growth areas and research gaps in Additive Manufacturing (Figure 2). The curves were normalized to show the data relatively. The articles that were published in the year 2023 have not yet been incorporated into the graph.

The evaluation of trends in AM research between 2017 and 2022 depicts a dynamic and constantly changing landscape regarding the adoption and exploration of these technologies. MEX and PBF show a constant presence, while DED reveals a recent smoother evolution.

MEX traditionally attracted most studies. This interest is due to its accessibility and adaptability. MEX allows using diverse materials, including affordable plastics, making it ideal for rapid prototyping and small-scale production [6]. Furthermore, the reduced cost of MEX equipment has enabled its widespread adoption in academic and research environments [12].

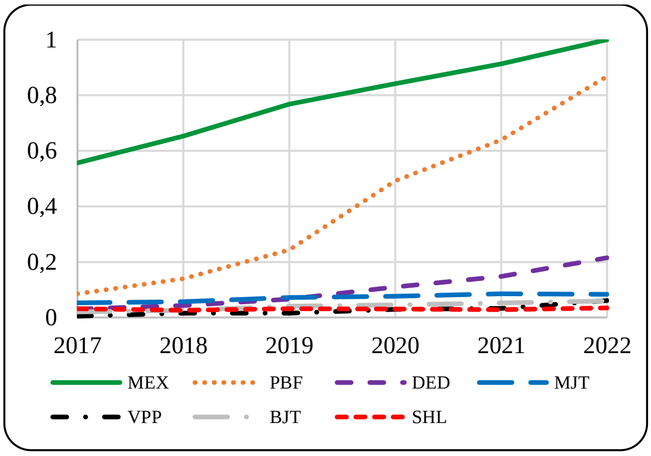

Figure 2. Comparison of publications of each AM technology. Source: adapted from [13]

On the other hand, PBF has shown significant growth in terms of research in recent years. Several factors contribute to this phenomenon. Firstly, PBF can produce high-density components, making it attractive for applications with fundamental mechanical strength [14]. Another relevant factor is PBF's ability to manufacture complex geometries and customize parts, an aspect precious in the automotive, medical, and aerospace industries [15]. The development of new materials specific to PBF and advances in simulation techniques have further boosted the expansion of this technology [14].

DED has also seen growth in research, although at a more moderate pace. This AM technology of metal is commonly employed for repairs, coatings, and production of large parts. The slower progression of DED can be explained by its lesser suitability for producing complex and high-precision parts compared to PBF [16].

However, despite the accelerated growth of PBF, MEX remains the most researched technology in Additive Manufacturing. In part, it occurs to its accessibility and versatility, which make it ideal for a wide range of applications, from rapid prototyping to small-scale production. Developing new materials for MEX can make this technology an even more valuable resource in the Additive Manufacturing scenario [6, 17].

Although Sheet Lamination remains relevant in specific applications and market niches, this article will not address the category in subsequent discussions. Other AM techniques, such as Material Extrusion, Powder Bed Fusion, and Directed Energy Deposition, have attracted greater interest from the scientific and industrial community due to their versatility and ability to process a broader range of materials and applications.

COSTS – During the planning and selecting of the appropriate process for a specific application, the relationship between cost and quality of parts manufactured by AM plays a crucial role [6]. Several factors, such as part complexity, the material used, AM technology employed, and specific project requirements, influence this relationship:

a. Part complexity: Complexity can increase production costs due to fabrication time, material consumption, and post-processing needs [6, 18, 19].

b. Material selection: High-quality materials typically cost more but provide superior mechanical, thermal, and durability properties and better surface finish. Material reuse and waste are significant points as they affect production costs [6, 19, 20].

c. Technology selection: Some AM technologies provide greater dimensional accuracy and surface quality but may have higher equipment and operational costs. Other technologies may be more accessible but compromise part quality and accuracy [6, 19, 20].

d. Specific project requirements: Specific requirements, such as dimensional tolerances, mechanical strength, and thermal properties, can affect cost. Projects that require high precision and performance may have higher costs due to the need for post-processing, heat treatment, and strict quality control [6, 18].

e. Production volume: AM can offer high quality at a relatively low cost for small-scale production and rapid prototyping compared to traditional manufacturing. However, for larger production volumes, unit costs may increase due to the speed and efficiency limitations of the AM process [6, 21, 22].

Two main factors were considered to evaluate and compare the costs associated with manufacturing parts using traditional manufacturing and Additive Manufacturing techniques: production volume and part complexity. With this approach, it is possible to observe the advantages and disadvantages of each method more clearly in terms of cost, assisting in decision-making about which technique is most suitable for a specific application [18]–[22].

Figure 3 shows how the price per unit of a specific component tends to vary when dealing with different production volumes for Traditional and Additive Manufacturing techniques. The graph helps identify the point at which one becomes more cost-effective than the other (breakeven point). Traditional manufacturing can be more economical for large-scale production, while AM can offer cost benefits for smaller and customized batches.

From another perspective, Figure 4 explores the relationship between cost and the increasing complexity of manufactured parts. The graph shows how the complexity or customization can affect the final cost per unit of traditional and Additive Manufacturing techniques. Generally, AM can be more advantageous for complex geometries by offering lower costs. In comparison, traditional manufacturing may be more suitable for simpler designs reaching lower costs when compared to AM.

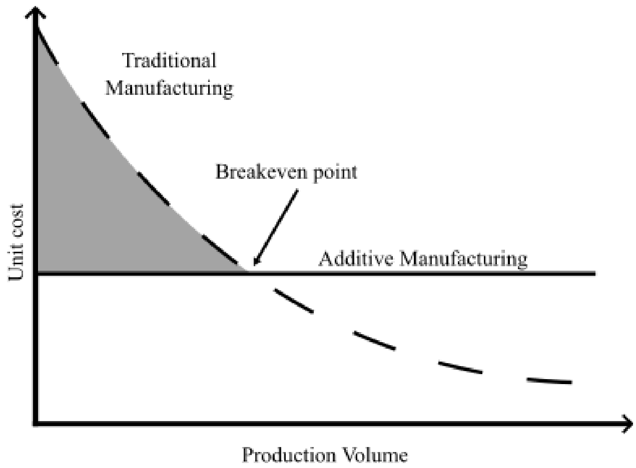

Figure 3. The behavior of traditional manufacturing and AM concerning production scale and cost.
Source: adapted from [18]–[22]

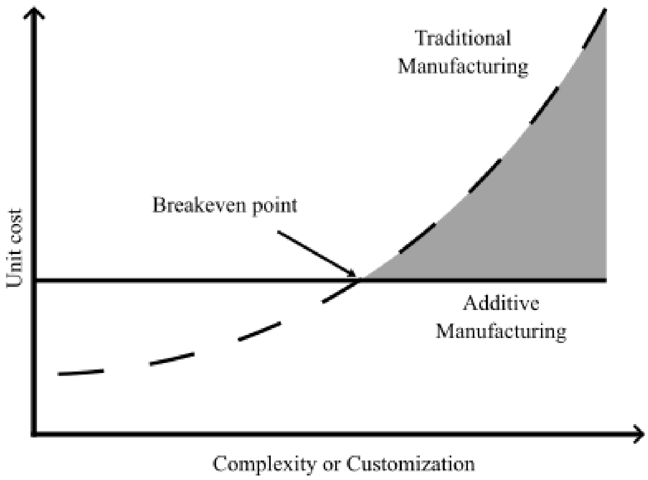

Figure 4. The behavior of traditional manufacturing and AM concerning capacity of customization and cost.
Source: adapted from [18]–[22]

In the two graphs presented, it is highlighted the areas where the cost of manufacturing per unit proves to be lower in Additive Manufacturing, when compared to Traditional Manufacturing.

By analyzing both graphs together, it is possible to obtain a complete perspective of situations where each manufacturing technique is more appropriate in cost, considering both production volume and part complexity. This interpretation assists in decision-making and choosing the most suitable method for each specific application, ensuring the ideal balance between quality and cost.

MECHANICAL PROPERTIES – The mechanical properties of materials produced by Additive Manufacturing technologies exhibit significant variations among different categories due to differences in material deposition or solidification processes. Comparing these properties can be challenging as they depend on part geometry, layer deposition orientation, process parameters (temperature, cooling time, particle size, and density), material type, and quality of the produced part [6]. In that way, consulting research articles and technical reports is advisable to obtain detailed information on the mechanical properties of each category [23]. The mechanical properties can heavily depend on the materials used and the specific process conditions [6].

Facing that, Table 1 aims to present a general ranking comparing some characteristics among the available AM techniques. The summarization compares the overall mechanical performance and presents information regarding the types of post-processing requested, surface finishing, costs, production capacity, types of material, and operating volumes. Remembering that this generalization may not apply to all cases is important. The final properties of each process must be analyzed case by case to consider the product's peculiarities.

The provided ranking is a simplification and should be interpreted with caution case by case. Although the summary does not contemplate specific situations of each technology, many factors are common and can bring fundamental reflections during manufacturing, such as:

a. Quality and density of parts: Some AM processes, such as PBF, produce parts with densities similar to those obtained by traditional manufacturing methods, resulting in greater mechanical strength [6, 23]. In contrast, processes such as MEX generate parts with higher porosity, which can reduce mechanical strength [24].

b. Type of material: Some AM processes are compatible with various types of materials, such as metals and their alloys, while others are more used for polymeric materials, which have lower mechanical strength compared to metals [25].

c. Process control: Some additive manufacturing processes, such as PBF and directed energy deposition (DED), offer better control over process parameters, resulting in parts with superior mechanical properties [26, 27]. These processes allow precise control over fusion energy and cooling rate, which affects the microstructure and, consequently, the mechanical strength of the manufactured parts [28, 29].

d. Post-processing: Some additive manufacturing processes require minimal post-processing, while others require additional steps such as sintering or heat treatment [30]. The effectiveness of these post-processing processes influences the final mechanical strength of the produced parts [6].

Table 1. Summary of properties and characteristics of the available AM technologies

Category	**Mechanical Performance Scale**	**Common Post-Processing**	**Surface Finish**	**Costs**	**Production Capacity**	**Types of Material**	**Operating Volume Range (min – max) [mm]**
PBF [23]	1st	PP3, PP5, PP8, PP9	++	$$$	++	Polymer, Metal	250 x 250 x 325 400 x 400 x 400
DED [31]	2nd	PP3, PP5, PP8, PP9	+	$$$	+	Metal	735 x 650 x 560 1040 x 610 x 3890
BJT [32]	3rd	PP2, PP3, PP6, PP7	++	$$	+++	Polymer, Metal, Ceramic	160 x 65 x 65 800 x 500 x 400
MEX [33]	4th	PP1, PP5, PP9	++	$	++	Polymer, Metal, Composite	220 x 220 x 250 500 x 500 x 500
MJT [34]	5th	PP5, PP8, PP9	+++	$$$	++	Polymer, Metal, Ceramic, Composite	298 x 185 x 203 490 x 390 x 200
VPP [35]	6th	PP3, PP4, PP5	+++	$	++	Polymer, Ceramic	115 x 65 x 165 650 x 750 x 550

Category caption: PFB - Powder Bed Fusion, DED - Directed Energy Deposition, BJT - Binder Jetting, MEX - Material Extrusion, MJT - Material Jetting, VPP - Vat Photopolymerization.

Post-Processing caption: PP1 - Chemical or thermal smoothing, PP2 - Infiltration, PP3 - Blasting, PP4 – Post Cure, PP5 - Support removal, PP6 - Coating or polishing, PP7 - Sintering, PP8 - Heat treatment, PP9 - Machining.

Source: adapted from [23, 31–35]

Table 1 shows that the PBF category demonstrates the highest mechanical performance when contrasted with other AM categories. It is important to emphasize that such performance is only obtained after a stress-relief heat treatment (PP8), which is indispensable for this category. The accumulated stress results from the printing process, which involves heating and rapidly cooling the material. PBF stands out due to its high printing resolution, the high relative density of the material, potential stress relief through heat treatment, and precise control over the material's microstructure. These attributes collectively contribute to its superiority in terms of mechanical response [23].

PBF and DED processes are the costliest among all AM categories. Several factors contribute to this reality. First, PBF and DED require sophisticated and high-value equipment. Furthermore, the materials used in these processes have complex and precise shapes and are of high quality, which raises the cost of inputs. Another element to consider is the post-processing process, which is mandatory for PBF and often required for DED. Finally, the technical knowledge required to operate and maintain these systems also contributes to high operating costs. Therefore, although PBF and DED provide high performance in terms of mechanical characteristics and the ability to manufacture complex components, these benefits come with significantly higher costs than other AM techniques.

The following discusses some post-processing procedures that are more specific to some AM technologies:

a. Chemical or Thermal Smoothing (PP1): Primarily used in components manufactured by MEX. It is used to smooth rough surfaces, which is characteristic of this category. This smoothing improves the appearance and can increase wear resistance and reduce flow resistance, which is essential in fluid flow components [33].

b. Infiltration (PP2): Mainly used in components manufactured by BJT. It consists of infiltrating a material to increase the strength, hardness, and other mechanical properties of porous and fragile parts in their green state [32].

c. Post-Cure (PP4): Mainly used as post-processing for VPP. It is crucial to stabilize the structure and improve the hardness and durability of the material. The part may remain brittle or deform under stress [35].

d. Sintering (PP7): Used as post-processing for parts manufactured by BJT. The aim is to consolidate the powder material into a solid, dense structure. This is critical to ensure the strength and integrity of the part, improving its mechanical properties [32].

Another property that plays a crucial role in AM is anisotropy, which refers to the material characteristic of exhibiting different behaviors and responses in different directions after being loaded. An anisotropic material has physical or mechanical properties that vary depending on the orientation in which they are measured [6], and it can affect AM components' performance in various ways:

a. Mechanical properties: Due to the layer-by-layer deposition nature of AM processes, components exhibit different mechanical properties in various directions. Product development must study how printing orientation and loads impact strength and durability [25].

b. Porosity and defects: The material deposition and fusion process can lead to the formation of oriented porosity and defects [25].

c. Surface roughness and finishing: Variation occurs depending on the direction of the layers, which affects the appearance, performance, and life of the component, especially in applications where surface contact is necessary [36]. Fatigue life is also a crucial factor to consider in the earlier stages of development.

d. Residual stresses: The heating and cooling process generates residual stresses in the material, which can promote deformations and possible failures. These stresses vary depending on the layers' orientation and the part's geometry [37].

Optimizing the manufacturing process, considering the part's orientation, the type of material, and the process conditions, is essential to reduce the effects of anisotropy in components manufactured by AM [6]. Additionally, applying post-treatments such as heat treatment, stress relief, and surface finishing can help improve the isotropy of material properties and increase the quality and durability of the manufactured components [38]. In that way, Design for Additive Manufacturing guidelines may aid the process of choosing the best technology based on each application.

DESIGN FOR ADDITIVE MANUFACTURING (DfAM) – The growing adoption of Additive Manufacturing requires a differentiated approach to product design and development, taking advantage of the unique capabilities offered by these technologies [6]. In this context, Design for Additive Manufacturing (DfAM) emerges as a set of principles and practices that seeks to optimize the design of components specifically for AM. Sustainability is a fundamental aspect when designing for Additive Manufacturing, involving the efficient use of resources, minimizing environmental impact, and promoting environmentally responsible practices [39]. When designing components focusing on sustainability, designers consider several aspects, including reducing material waste. Additive Manufacturing produces less waste compared to traditional manufacturing processes [6]. For instance, optimizing the shapes of components minimizes the amount of material required and reduces waste generated during manufacturing [39].

The efficient use of energy is also an important aspect. Choosing appropriate technologies and process parameters can decrease energy consumption in manufacturing [6]. In addition, optimizing the component's geometry can result in lighter parts, which, in turn, can reduce energy consumption during product use [39].

Considering the selection of sustainable materials is another critical factor. AM allows for the use of a range of recyclable, biodegradable, or low-environmental impact materials, considering the component's application and functional requirements [6].

In a similar direction, topological optimization plays a significant role in DfAM, creating more efficient and sustainable structures and maximizing available resources [40]. Topological optimization is a computational simulation tool that calculates the ideal distribution of the material in a design space, considering load and performance constraints [41]. AM has widely used this technique to develop lightweight and high-strength components and reduce material and energy consumption during manufacturing [42].

This simulation process is particularly prominent, especially in aerospace and automotive applications, where weight reduction is crucial to improve energy efficiency [6]. Applying this technique in components manufactured by AM allows for greater geometric freedom and the possibility of creating complex structures that would be impossible to manufacture by conventional methods [43].

Topological optimization with DfAM allows for greater functionalities integration into the parts, such as incorporating cooling channels or combining multiple parts into a single component [44]. Reducing the number of parts and assembly processes also reduces the product's environmental footprint [39].

As seen, it is essential to use advanced tools and techniques that help optimize the process to achieve better results in Additive Manufacturing and take advantage of the capabilities of topological optimization. Among these tools, simulation software stands out as an effective solution to address challenges and improve the quality of manufactured parts.

Figure 5 illustrates a topological optimization application in an air suspension piston [45]. The image demonstrates how topological optimization can lead to complex designs, unachievable by traditional manufacturing methods, highlighting the invaluable value of integrating Additive Manufacturing and computational simulation. From left to right: the original part, modeled in CAD (Computer Aided Design) software; the result of the topological optimization; and the final piece after a redesign, taking manufacturing and finishing conditions into account.

COMPUTATIONAL SIMULATION – The role of computer simulation in the optimization and development of Additive Manufacturing has been increasingly important [6]. Through modeling and analysis of manufacturing processes in virtual environments, computer simulation offers valuable insights into the relationship between process parameters, part quality, and production efficiency [46]. It can aid in the use of AM and the advantages of its application in different AM processes by:

a. Predicting and optimizing mechanical properties: This can help predict how different process parameters and materials affect the mechanical properties of produced parts, allowing for adjustments and optimizations before production. It can result in parts with higher strength, durability, and performance in specific applications [6].

b. Reducing defects and failures: Can be used to identify areas where the part may be susceptible to defects, such as porosity, cracks, or distortions. It allows for adjusting the design or process parameters to reduce the likelihood of failures and improve the component's quality [47].

c. Minimizing residual stresses and deformations: This can predict the formation of residual stresses and deformations during the AM process, allowing for adaptation of process parameters and mitigation strategies, such as using supports or post-processing heat treatments [37].

d. Optimizing structures and topologies: Simulation tools can be combined with topology optimization techniques to create lightweight and high-performance components, taking advantage of the design freedom offered by Additive Manufacturing. It can result in parts with better strength-to-weight ratios and higher material efficiency [6].

e. Reducing development time and costs: This can help reduce development time and costs associated with producing prototypes and experimental tests, allowing for virtual optimization of processes and designs before physical manufacturing [48].

f. Planning and monitoring the process: This can help plan and monitor the manufacturing process, identifying defects and improving the efficiency, quality, and performance of produced parts [46].

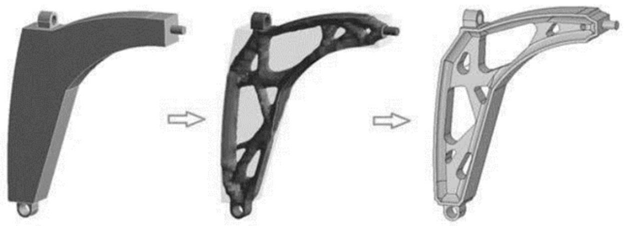

Figure 5. Application of topological optimization to a suspension arm. Source: adapted from [45]

For each category of AM, computer simulation can be auxiliary in diverse ways:

1. <u>Binder Jetting (BJT)</u>: Simulation can improve the understanding of interactions between the binder and powder materials, predict the density and porosity of

the part after sintering, optimize the binder deposition process, and the drying strategy to achieve better quality and consistency of parts. It can also help predict the shrinkage and density of parts during sintering and the distribution of stresses and defects in the material, allowing for the optimization of process parameters and material composition, improving part quality, and minimizing failures [32].

2. Directed Energy Deposition (DED): In this case, simulation can predict and control the geometry of the deposited material bead, microstructure, and residual stresses, aiding in selecting suitable process parameters such as beam power, feed rate, and travel speed. It results in manufacturing parts with optimized mechanical properties and microstructures [49].

3. Material Jetting (MJT): For MJT, simulation can analyze the material distribution, layer interaction, and control of the jetting process, improving part quality and reducing the need for rework and post-processing [50].

4. Material Extrusion (MEX): In MEX, simulation aids in the optimization of extrusion conditions such as extrusion speed, temperature, and layer height, as well as predict deformation and adhesion between layers, contributing to improving part quality and strength [51]. Specifically for metallic parts, simulation can predict anisotropic predictions, which allow designers to compensate models before the manufacturing phase.

5. Powder Bed Fusion (PBF): In PBF processes, simulation tools are indispensable to minimize residual stresses, deformations, cracks, and porosity, during printings. The software also aids in the optimization of fusion strategies and processing conditions such as laser power, scanning speed, and layer thickness to obtain high-quality and high-strength parts. This analysis package contributes to part orientation decisions, process parameters calibration, and support strategies optimization, minimizing deformation and defects during production [52].

6. Vat Photopolymerization (VPP): For VPP techniques, computational simulation can assist in optimizing exposure parameters and selecting the most suitable photopolymerizable material. In addition, it can predict the distribution of residual stresses and distortions, helping to minimize defects and failures in the produced parts. This allows for optimizing the orientation of parts and the position of supports, improving dimensional accuracy, and minimizing the need for post-processing [35].

The industry has benefited significantly from computational simulation in AM, standing out as a powerful tool in optimizing manufacturing processes and improving the quality of parts produced [53]. Computational simulation shows its versatility and potential to overcome specific challenges in various categories of AM, including Binder Jetting, Directed Energy Deposition, Material Jetting, Material Extrusion, Powder Bed Fusion, and Vat Photopolymerization [32, 35, 49–52].

The growing trend of computational simulation in AM signals an imminent transformation in the automotive industry, especially in the search for greater sustainability [29]. Computational simulation is a fundamental catalyst for optimizing the use of materials and reducing vehicle weight [54] and leads to significant advances in energy efficiency, leveraging a more sustainable future [55].

Therefore, computational simulation and AM emerge as indispensable tools for shaping the future of the automotive industry. These technologies together have the potential to drive innovation and sustainability in this sector [23].

CONCLUSION

Throughout this study, a series of information and analyses were presented on Additive Manufacturing and Computational Simulation, illustrating the intersection of these two powerful technologies and how their interaction can influence the industry. Based on current standards, such as ISO/ASTM 52900, and emerging concepts of AM, this work explored current research trends in various AM categories, with a focus on Material Extrusion (MEX), Powder Bed Fusion (PBF), and Directed Energy Deposition (DED).

Our cost analysis highlighted the main factors that can influence AM manufacturing costs and made a qualitative comparison with the costs involved in traditional manufacturing. This analysis is vital to understand AM's economic viability and assess where and how it can be most effectively applied.

In evaluating the mechanical properties of each AM category, it was possible to separate and rank the categories, relate them to their main post-processing methods and materials used, and generalize the costs involved in each of the categories. It was also noted that the variation in mechanical properties is due primarily to anisotropy. These differences highlight the need to choose the most suitable AM category for each specific application to maximize manufacturing effectiveness.

We also explored the concept of DfAM, focusing on the technique of topological optimization. Implementing DfAM is crucial to make the most of the advantages of AM, allowing the creation of complex and efficient parts that would be difficult to manufacture by traditional means.

Finally, we highlighted the importance of computational simulation in developing AM-manufactured components. Through simulation, it is possible to predict and optimize a range of factors, from the quality and mechanical properties of parts to the efficiency of the manufacturing process. However, despite the evident advances and benefits, the widespread adoption of AM and computational simulation in Brazil still faces challenges. The need for adequate infrastructure, training, and education in AM & computational simulation are obstacles that must be overcome. The integration of AM with computational simulation has immense potential to drive sustainability in the automotive industry. By enabling the production of lighter and more efficient parts and optimizing the use of materials, these technologies can contribute significantly to reducing carbon emissions and to the energy efficiency of vehicles.

In short, the future of AM and computational simulation appears promising, mainly when applied to the automotive industry. However, continuous effort is needed to overcome the existing barriers and to promote broader adoption of these technologies. In doing so, we can expect a more efficient, innovative, and sustainable industry.

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