processes

Article

Towards Sustainability in Hydraulic Machinery Manufacturing by 3D Printing

Abel Remache [1], Modesto Pérez-Sánchez [2,*], Víctor Hugo Hidalgo [3], Helena M. Ramos [4] and Francisco-Javier Sánchez-Romero [5,*]

1 Industrial Design Department, Facultad de Ingeniería y Ciencias Aplicadas, Universidad Central del Ecuador, Quito 170129, Ecuador; apremache@uce.edu.ec
2 Hydraulic Engineering and Environmental Department, Universitat Politècnica de València, 46022 Valencia, Spain
3 Laboratorio de Mecánica Informática, Facultad de Ingeniería Mecánica, Escuela Politécnica Nacional, Quito 170517, Ecuador; victor.hidalgo@epn.edu.ec
4 Civil Engineering Research and Innovation for Sustainability (CERIS), Department of Civil Engineering, Architecture and Environment, Instituto Superior Técnico, University of Lisbon, 1049-001 Lisbon, Portugal; hramos.ist@gmail.com or helena.ramos@tecnico.ulisboa.pt
5 Rural and Agrifood Engineering Department, Universitat Politècnica de València, 46022 Valencia, Spain
* Correspondence: mopesan1@upv.es (M.P.-S.); fcosanro@agf.upv.es (F.-J.S.-R.)

Abstract: Material wear, maintenance costs, performance, efficiency, and corrosion are some of the issues that turbomachinery impellers may encounter. The optimization of impellers through additive manufacturing (AM) has been the focus of extensive research, aiming to address these challenges in turbine, pump, compressor, fan, and mixer components. This research aims to identify and analyze the main techniques currently being developed to tackle several of these issues. Evaluating the published research, the methodology highlights various AM techniques applied to impellers and related components, as well as the diverse materials used in functional system elements. The analysis revealed that the most commonly used additive manufacturing technologies for the production of turbomachinery components are FDM, with a 22% application rate, and powder bed fusion technology, accounting for 35%, utilized for high-complexity parts and even superalloys. Although more expensive, these technologies employ materials with superior resistance capabilities, surpass the limitations of conventional machining, optimize manufacturing times, and allow for the fine-tuning of multiple parameters. In terms of wear and corrosion resistance, materials such as Inconel 718 exhibited a loss of less than 0.1 mpy (mils per year) in highly corrosive environments, representing a significant improvement over traditional materials.

Keywords: impellers; turbomachinery; additive manufacturing; 3D printing; materials; corrosion

check for updates

Citation: Remache, A.; Pérez-Sánchez, M.; Hidalgo, V.H.; Ramos, H.M.; Sánchez-Romero, F.-J. Towards Sustainability in Hydraulic Machinery Manufacturing by 3D Printing. *Processes* **2024**, *12*, 2664. https://doi.org/10.3390/pr12122664

Academic Editors: Diane Mynors and Raul D. S. G. Campilho

Received: 27 October 2024
Revised: 18 November 2024
Accepted: 20 November 2024
Published: 26 November 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Turbomachinery encompasses a variety of equipment, including turbines, pumps, compressors, fans, and mixers, and plays a vital role in numerous industrial applications [1]. However, it faces significant challenges, such as material degradation, the need for resource efficiency, maintenance expenses, and the pursuit of optimal performance [2,3]. Failures in turbomachinery are frequently caused by physical factors in the operating environment, with impeller deterioration and damage to adjacent components often attributed to corrosion (related to the chemical attack from the environment) [4,5], erosion (related to the quantity and size of erosive particles or liquid droplets) [6], and cavitation (due to fluid pressure changes) [4]. Studies suggest that the absence of specific classification criteria for material properties suited to their intended applications is a major factor contributing to turbine wear. This issue is compounded by limited research on frictional heating, surface interactions, and contact forces [7]. Expanding the range of available materials and improving knowledge on material selection could significantly alleviate these challenges.

Recent studies have achieved promising results by focusing on critical operational aspects of turbomachinery. For instance, improvements in surface finish and reductions in roughness have been shown to enhance resistance to water droplet erosion (WDE) [8] and to mitigate pressure effects, thereby preserving efficiency [9,10]. Vibrations, which influence lifespan, fatigue failures, and efficiency [11], are frequently caused by cavitation and resonance. Factors such as overspeed and prolonged operation further contribute to wear and are associated with increased vibrations [12]. Currently, efforts are being made to identify failures through algorithms and Industry 4.0 elements, such as machine learning [13], Industrial Internet of Things (IIoT) [14], additive manufacturing (AM), digital twins, among others [15].

Centrifugal compressors often fall short in applications where the process fluid is dense or liquid [16], a crucial consideration for energy systems. Energy systems are fundamental in turbomachinery as they must be reliable; thus, new processes are being optimized. For example, the use of supercritical CO_2 (sCO_2) in energy systems promises efficient, compact, and reliable energy [17]. The impeller, a key component of turbomachinery, primarily faces issues with corrosion [18]. When operating in contact with liquids and solids, the wear from erosion becomes significant, directly affecting the materials used [19].

Erosion degrades materials, leading to losses in performance, productivity, and maintenance efficiency. In centrifugal pumps, the suction surface of the blades is generally most affected by erosion [20]. Erosive wear in turbomachinery can be mitigated by minimizing the quantity and size of erosive particles, though each working environment is unique and presents distinct characteristics. It is crucial to use appropriate materials or coatings resistant to erosion [4]. Particulate characteristics have a direct relationship with erosive damage, reducing pump performance. Larger and more angular particles cause more severe erosion damage. Moreover, particle shape is known to impact turbomachinery performance less significantly than particle size and concentration [21]. In centrifugal pumps, performance diminishes with increased sediment concentrations.

In terms of corrosion, defects become evident over time due to workload and the rotational performance of the impellers [22]. In corrosive and aggressive environments, it is essential to use improved and optimized materials suitable for the specific conditions. Efforts should be made to reduce or eliminate sources or conditions leading to the formation of corrosive compounds [4]. Enhancements in manufacturing methods, chemical compositions, heat treatments, and surface coatings have led to the development of corrosion-resistant turbomachinery components. The mechanical properties of impellers before and after exposure to corrosion have been shown to remain unchanged, indicating that the effects are predominantly external [23].

Corrosion is an electrochemical process that involves oxidation and material loss from metallic surfaces. Thus, polymeric materials and composites are being explored as solutions to this issue. Impellers are critical components that directly influence the performance of turbomachinery; their complex geometries, operational speeds, flow patterns, and fluid compositions typically lead to non-uniform wear [24]. In this context, topological optimization and the use of AM have provided practical solutions. For instance, Laser Metal Deposition (LMD) has enabled the production of optimized parts with complex geometries, maintaining or even exceeding the mechanical properties of conventionally manufactured parts while also offering the required corrosion resistance [25].

Cavitation significantly influences the design and operation of pumps, particularly as operational speeds increase [26]. Research has shown that cavitation typically initiates at the blade's leading edge due to a local pressure drop [27]. Optimizing the shape of the impeller blade's leading edge using AM can enhance performance and mitigate the effects of cavitation [28]. Cavitation often arises from complex flow dynamics, affecting the efficiency, safety, and stability of turbomachinery [29]. In pumps, cavitation is characterized by persistent noise in the suction section, followed by increased vibration and noise levels, along with reduced total head and output capacity [30]. When cavitation ranges increase, pump performance tends to decline significantly [31].

Flow dynamics are vital in the design of turbomachine components. For instance, various types of turbomachinery can be applied, studied, and analyzed according to the Japikse and Baines design window, as illustrated in Figure 1 [1].

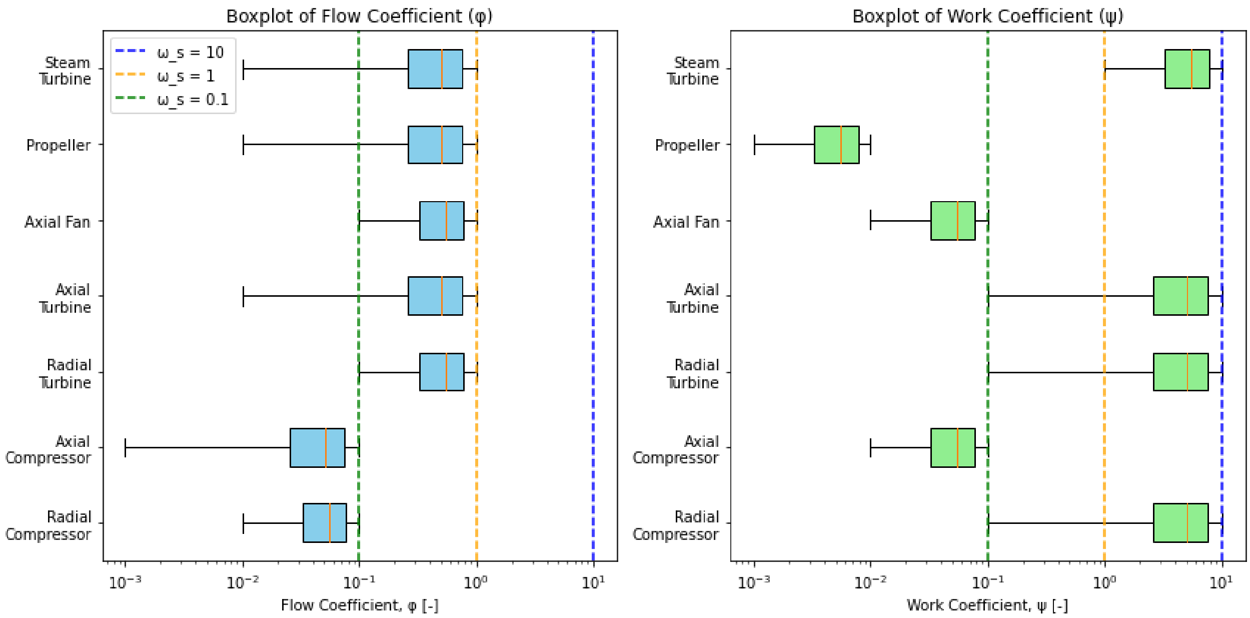

Figure 1. Turbomachines design windows.

Optimizing impellers through advanced manufacturing has become a focal area of research to address the challenges mentioned previously. Material removal manufacturing techniques have shown promising results. The advent of new manufacturing methods and materials has facilitated improvements in addressing specific issues; for instance, the use of unspecified materials is a known cause of impeller failure [24]. Vibration reduction through piezoelectric materials can semi-actively dampen vibrations [32], and the use of carbon nanocomposites such as carbon nanofibers, carbon nanotubes, and graphene has generated positive outcomes in vibration management [33]. Corrosion effects on compressor impellers can be mitigated through surface treatments and coatings [34,35], though certain thermal treatments may induce deviations in blade geometry [36].

Polymeric materials based on epoxy resin with silicon carbide exhibit the highest wear resistance, while silumin shows lower wear resistance. Testing on terrestrial pumps has revealed that parts made from electrocorundum in an epoxy-phenol-formaldehyde bond, compared to parts made from wear-resistant cast iron, can increase the lifespan of pumps by three to eight times [37].

In Computed Numeric Control (CNC) processes, thermoplastics and composites, such as Polyether-ether-ketone (PEEK) and Polyphenylene sulfide (PPS), with and without reinforcements, have been used as suitable options for manufacturing impellers [38]. PEEK and epoxy reinforced with carbon fiber are the most commonly used composites for impeller production via this method, but they have resulted in material waste and excessive energy consumption [38,39].

AM has revolutionized numerous industries. In the medical and dental sectors, SLA and DLP technologies enable the production of customized devices, anatomical models, and prosthetics with high precision and biocompatibility. In the automotive and aerospace fields, AM facilitates the creation of lightweight and functional components using shape-memory polymers and composite materials [40]. It has also allowed the reproduction of discontinued parts through 3D scanning and modeling, generating components that are otherwise unavailable in the market. Additionally, AM proves valuable for low-scale production, rapid tooling, and the development of digital inventories, optimizing supply chains [41]. The production of carbon fiber-specific parts and generative design are highly valued for their durability and adaptability. Furthermore, AM enables the manufacturing of complex tools and molds for injection molding and casting, significantly accelerating production processes [41,42].

In the space sector, 3D printing techniques such as Binder Jetting and FDM are being explored to produce robust structures capable of withstanding extreme temperature fluctuations and meteoroid impacts. These methods ensure that structures maintain adequate thickness and that printing equipment remains resilient under vacuum conditions [42].

From a sustainability perspective, the use of biopolymers and recyclable materials in 3D printing reduces environmental impact. AM also fosters innovation through its integration into education and research. To meet sustainability requirements, AM contributes to reductions in energy consumption, production costs, lead times, material waste, and greenhouse gas emissions while promoting circular economy practices [43]. However, AM does not completely eliminate waste generation, and some evidence suggests that its energy consumption may exceed that of casting and injection molding processes [44,45]. Efforts to make AM more sustainable are ongoing, focusing on areas such as support structure optimization, print orientation, post-processing, and design strategies [46]. These measures can enhance eco-efficiency; for example, in the transportation sector, AM-produced components are lighter, reducing fuel consumption [47].

Most AM processes require post-processing steps, ranging from polishing to heat treatments and coatings, to meet quality standards for aesthetics, functionality, and durability [48]. A significant challenge in the post-processing of metal structures lies in its high cost and time intensity [49]. However, the integration of big data, machine learning, and digital twins has the potential to reshape the AM landscape, driving innovation, sustainability, and efficiency [50].

The application of additive manufacturing has demonstrated enhancements in efficiency and effectiveness in impellers and is recognized as an efficient method for producing components that are challenging to machine [51]. One of the advantages of additive manufacturing is the variety of materials it employs, such as polymers, metals, composites, and ceramics, in addition to generating complex geometries [52]. However, significant differences exist among 3D printing methods; for example, Stereolithography (SLA) and MultiJet (MJ) printing can offer more suitable surface finishes due to their production processes [53]. Studies related to microstructural defects produced by this process are still sparse, though several mention that the microstructure does not undergo radical changes [54–56].

Polymeric Composite Materials (PCMs) have become popular due to their anticorrosive properties and competitiveness with traditional materials, though market competition remains low. Additive manufacturing (AM) has opened a new window of application in hydraulic machinery, creating more valuable components and materials with reliable performance, addressing many of the Sustainable Development Goals (SDGs) [57].

In the specific context of turbomachinery and additive manufacturing, the current state of the art provides a deep understanding of advanced materials and innovative techniques used in impeller production. The integration of 3D printing in this field not only facilitates the direct creation of parts from digital models but also introduces a range of new possibilities for the design and optimization of critical components. However, this advancement also brings a series of technical challenges and issues that require innovative solutions and a rigorous approach. This review aims to thoroughly examine the different additive manufacturing methods applied in the production of turbomachinery components, evaluating both their advantages and limitations, and highlighting their practical application in real industrial scenarios. This analysis seeks to illustrate the current state of technology and identify emerging trends and future directions in this crucial field.

2. Materials and Methods

The methodology employed in this study is grounded in a comprehensive literature review, adhering to rigorous criteria and methodological recommendations established in the scientific literature. To ensure the validity, clarity, and utility of the analysis, the criteria proposed by [58] and the practical guidelines for methodological reviews outlined by [59] were applied. These methodological approaches are designed to enhance the precision and reproducibility of studies, ensuring that the conclusions drawn are robust and reliable. As a novelty, the methodology addresses an analysis of the mechanical and hydraulic behavior of non-classical materials in the manufacture of impellers.

In constructing the flowchart for the applied methodology, the guidelines established by [60] were followed, which delineate five critical phases in the documentary analysis process: (1) Identification and Initial Selection, where studies potentially relevant for further retrieval are identified and selected; (2) Initial Exclusion, where studies that are neither empirical nor involve both print and digital reading are excluded, ensuring that only research meeting these criteria is considered; (3) Detailed Evaluation, a phase in which a more thorough evaluation of the retrieved studies is conducted, retaining only those that surpass the preliminary selection criteria; (4) Further Exclusion, where studies employing inappropriate methodologies or unverifiable measures are eliminated to maintain scientific rigor; and (5) Final Inclusion, where studies that fulfill all the established methodological requirements are incorporated into the literature review. As a result of the rigorous application of these criteria, the scheme depicted in Figure 2 has been designed, illustrating the workflow and decisions made during the study selection process.

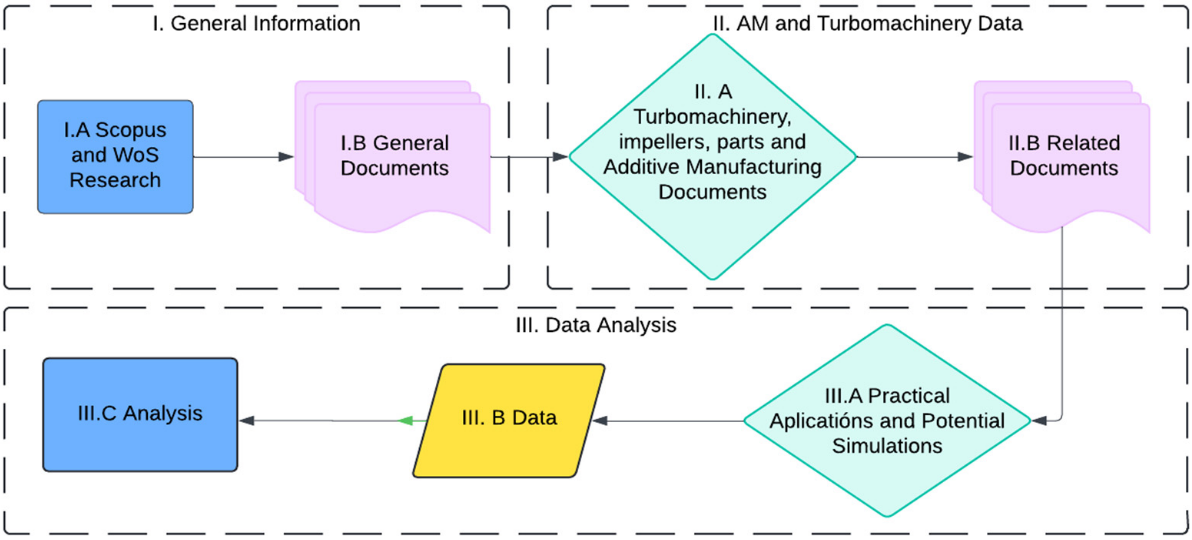

Figure 2. Flowchart of the applied methodology.

To organize and analyze the information gathered, three main groups were structured: (I) General Information, (II) Data on Additive Manufacturing (AM) and Turbomachinery, and (III) Data Analysis. These groups facilitated the systematic analysis and in-depth discussion of the findings from the review.

2.1. I. General Information

I.A Scopus and WoS Research: Initially, a general query related to the topic was conducted using search equations in the Scopus [61] and Web of Science (WoS) [62] databases, as well as high-impact articles. Reviews were excluded, and scientific articles, conference papers, conference reviews, and book chapters were considered.

Keywords and equations with Boolean operators were used as shown in Table 1. The search was conducted as follows: Impellers "AND/OR" 3D Printers, Impellers "AND/OR" 3D Printing, Impellers "AND/OR" Additive Manufacturing.

Table 1. Common materials in impellers used in additive manufacturing.

Keyword	Boolean Operator	Keyword
Impellers	AND/OR	Printers/3D Printing/Additive Manufacturing
Turbomachinery	AND/OR	Printers/3D Printing/Additive Manufacturing
DMLS-LPBF-SLM	AND/OR	Impellers/Turbomachinery/Turbomachines
FDM	AND/OR	Impellers/Turbomachinery/Turbomachines
SLS	AND/OR	Impellers/Turbomachinery/Turbomachines
DLP	AND/OR	Impellers/Turbomachinery/Turbomachines
Polyjet	AND/OR	Impellers/Turbomachinery/Turbomachines
SLA	AND/OR	Impellers/Turbomachinery/Turbomachines
BJP	AND/OR	Impellers/Turbomachinery/Turbomachines
BMD	AND/OR	Impellers/Turbomachinery/Turbomachines
EBM	AND/OR	Impellers/Turbomachinery/Turbomachines
MJF	AND/OR	Impellers/Turbomachinery/Turbomachines
LMD	AND/OR	Impellers/Turbomachinery/Turbomachines
Additive Manufacturing	AND/OR	Impellers/Turbomachinery/Turbomachines

I.B General Document Collection: A detailed collection of documents addressing a wide range of topics related to 3D printing, additive manufacturing, and turbomachinery was undertaken. This involved analyzing trends in scientific production over time and identifying the number of research studies conducted per year, which helped assess the scientific interest in these areas. Additionally, publications by country were reviewed to identify the main focuses of research and international collaboration. Finally, a co-occurrence analysis was conducted to map the relationships and dependencies between research studies, facilitating the identification of patterns and knowledge networks within the field.

2.2. II. AM and Turbomachinery Data

II.A Filtering of Documents Related to Turbomachinery and Additive Manufacturing: Once the general information was gathered, the process of filtering documents specifically relevant to the study commenced. This filtering focused on identifying studies centered on the design, manufacturing, and optimization of key turbomachinery components, such as impellers and blades, manufactured through additive manufacturing. Studies based on unverified simulations or using obsolete technologies were excluded to maintain a focus on recent and relevant empirical studies that reflect the current capabilities of the technology.

II.B Retrieval of Related Documents: From the initial filter, the compilation and organization of documents providing profound insights into the manufacturing and application of turbomachinery components via additive manufacturing were carried out. Information was classified based on the different types of additive manufacturing processes and the mixed processes used, allowing for a comparative evaluation of the various methodologies employed in the industry. This analysis included not only an examination of manufacturing techniques but also an assessment of their practical implementation, costs, challenges, and long-term benefits.

2.3. III. Data Analysis

III.A Filtering of Practical Applications and Potential Simulations: A second thorough filtering of the available documentation was conducted to identify studies presenting practical applications of 3D printing in turbomachinery. This filter particularly focused on those studies that, in addition to documenting the practical use of the technology, included simulations with a high potential for application in real-world scenarios. To ensure the validity and relevance of the information gathered, priority was given to studies published in higher quartile journals (Q1 and Q2), as these tend to offer more rigorous and reliable research. Only those studies that provided clear evidence of performance in real applications were included, ensuring that the derived conclusions were applicable and useful for the industry.

This approach not only allowed for a careful selection of the literature but also a robust validation of the presented simulations, ensuring that any theoretical or experimental model considered had a high likelihood of success in specific industrial applications. This established a solid foundation for analyzing the feasibility and comparative advantages of additive manufacturing in the production of turbomachinery components.

III.B Data Extraction: Subsequently, specific data from the selected studies were extracted. This process involved a meticulous compilation of key information, including the additive manufacturing methods used, the materials employed in the manufacturing, the parts of turbomachinery produced, and the speeds achieved. Comparative data were also gathered, allowing for an evaluation of improvements in the performance of these processes relative to traditional manufacturing methods or other advanced techniques.

Data extraction also focused on identifying significant improvements in terms of efficiency, cost, and quality of the produced components, as well as the durability and resilience of the 3D-printed materials. This enabled a detailed view of the impact of additive manufacturing on the overall performance of turbomachinery, providing critical information for the assessment of its adoption on a larger scale in the industry.

III.C Analysis: The analysis of the extracted data was conducted with a detailed and critical approach, evaluating both the feasibility and advantages of additive manufacturing methods in the production of turbomachinery components. This analysis included a comprehensive review of the selected documents, focusing on the different types of additive manufacturing processes, the materials employed, and specific characteristics such as corrosion resistance and the durability of the manufactured parts.

Possible improvements in process efficiency, as well as the practical applications of the printed materials in real-world scenarios, were discussed. Additionally, specific advantages associated with the different materials and printing technologies used were identified, evaluating their performance under typical operating conditions of turbomachinery. This analysis not only validated the simulations and practical applications identified in earlier stages but also elaborated an integral discussion on the potential improvements that additive manufacturing can offer in this sector. The results of this analysis are crucial for understanding the potential impact of these technologies on the turbomachinery industry and for guiding future research and applications.

The adopted methodology ensures a rigorous and systematic approach in the collection, filtering, and analysis of relevant information, leading to solid and applicable conclusions about the use of additive manufacturing in the production of turbomachinery components. This process, illustrated in Figure 2, ensured that the findings presented are of high relevance to both the scientific community and the industry.

3. Results and Discussion

3.1. I. General Information

The direct search related to impellers and AM technologies yielded 133 documents in Scopus and 96 documents in WoS, while the search linked to turbomachinery and AM technologies resulted in 188 documents in Scopus and 349 documents in WoS. According to Figure 3, it can be observed that from the year 2017, research in the subject increased, reaching its highest peak in 2021 and 2022, although it is notable that there is not a large amount of research in the area.

In the Scopus database, it is possible to verify the top 15 countries with the highest number of publications, with China, the United States, and India being the countries with the most significant contribution and research interest in this topic, as shown in Figure 4.

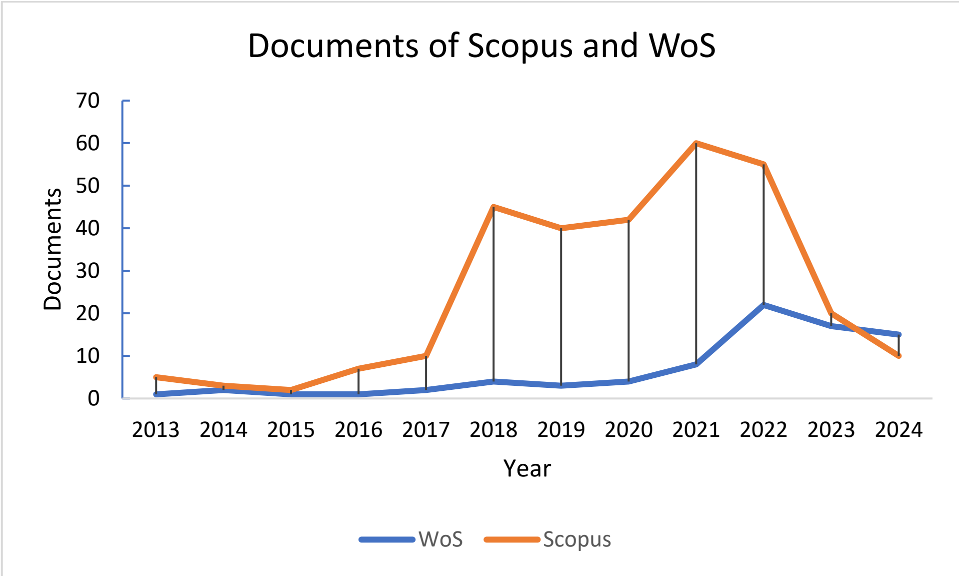

Figure 3. Documents related to the literature review from 2013 to 2024.

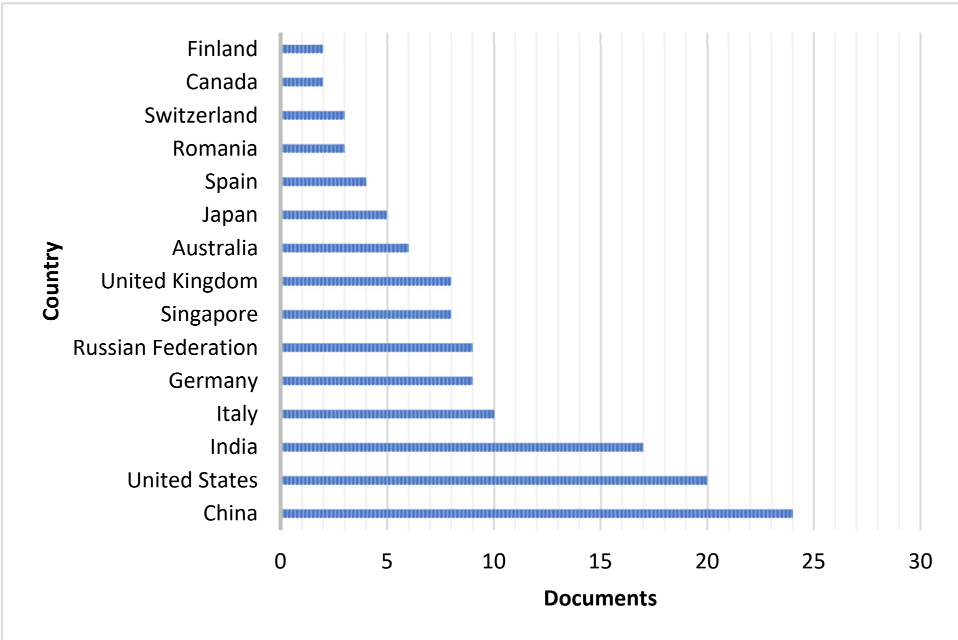

Figure 4. Documents by country related to the search up to 2024.

Using co-occurrence analysis through Vosviewer [63] with Scopus and WoS data, Figure 5 shows that four main clusters of connections have been generated: additive manufacturing, additives, 3D printers, and turbomachinery. The study relations focus on topics related to powder bed fusion technologies, design and topological optimization, characterization and use of materials, alloys, turbine design, among other main areas of study.

The density analysis (Figure 6) shows the most relevant points of study where the aforementioned topics are most evident. Materials and alloys in different 3D printing technologies are key points for researchers, while topology, design, and optimization are hot topics according to the published research.

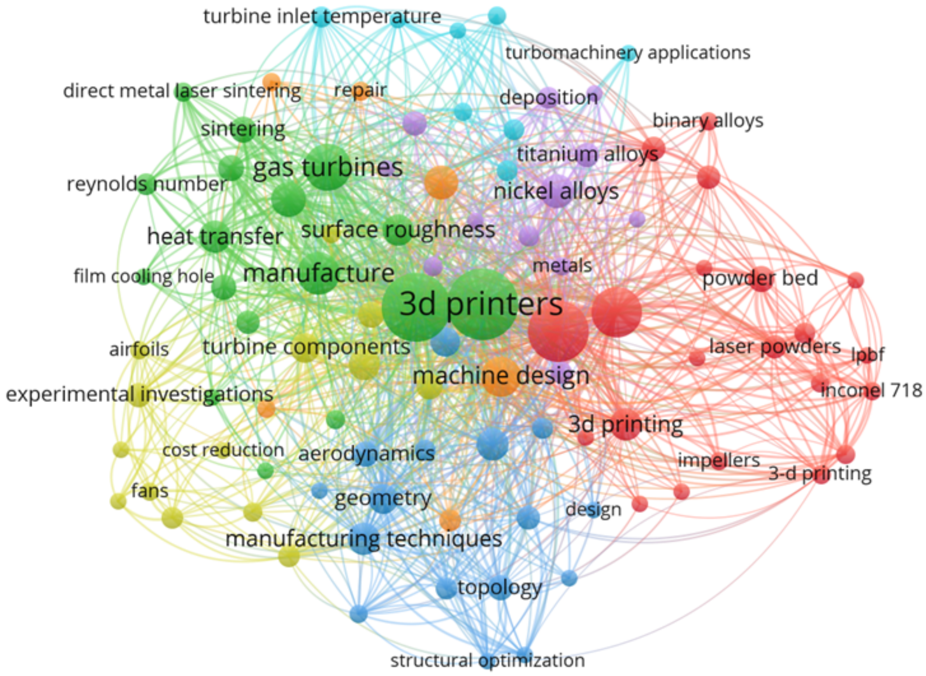

Figure 5. Co-occurrence analysis between documents and keywords.

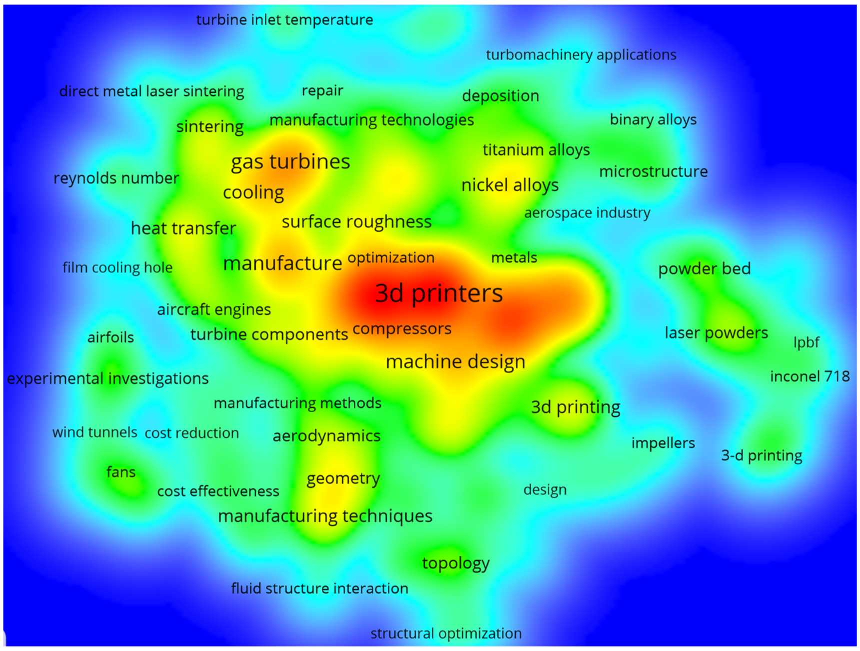

Figure 6. Heat map of scientific documents related to the review.

3.2. II. AM and Turbomachinery Data

Figure 7 shows that the most used technologies in the production of turbomachinery parts are DMLS, LPBF, SLM with an application rate above 3%, and FDM with a usage percentage above 20%. More advanced technologies, such as SLS and DMLS-LPBF-SLM, are increasingly used to produce high-complexity and performance parts. The adoption of additive manufacturing in the production of turbomachinery is limited by the number of materials used, their characteristics, and technological limitations. Despite these limitations, [64] mentions that there are good results such as optimized materials and more sustainable manufacturing processes.

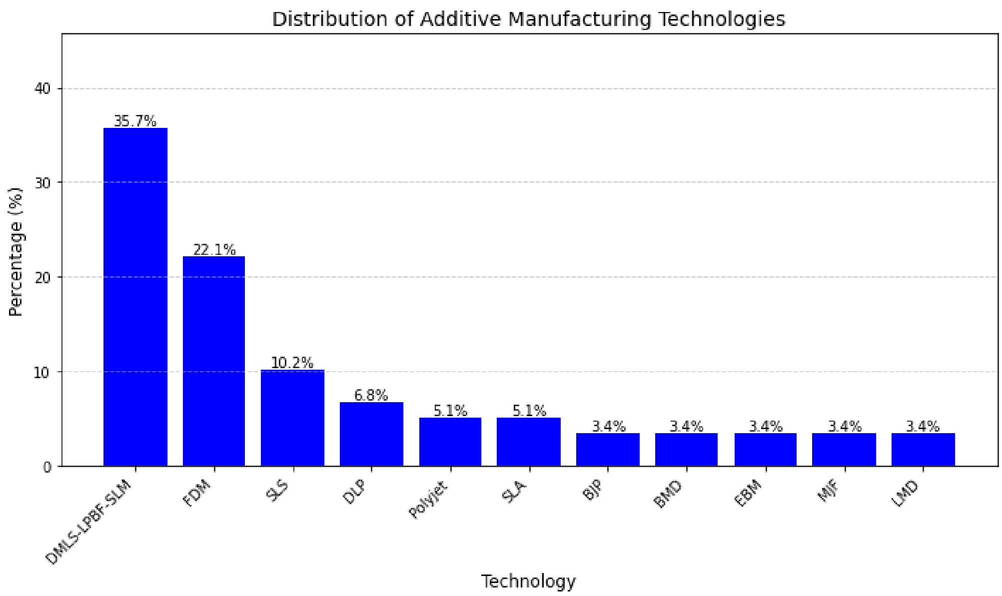

Figure 7. Use of additive manufacturing in turbomachinery.

According to [65], Powder Bed Fusion Technology encompasses various methods, including Direct Metal Laser Sintering (DMLS) or Selective Laser Melting (SLM), Selective Laser Sintering (SLS), Multi Jet Fusion (MJF), and Electron Beam Melting (EBM). The DMLS/SLM process, in particular, has demonstrated the ability to produce impellers with excellent dimensional accuracy, surface finish, and material strength, as shown in prints made from materials such as 17-4 PH, Ti-6Al-4V, Inconel 625, and Inconel 718 [66–68]. This method offers performance comparable to that of forged materials. For example, a study by [69] on impeller design revealed that 3D-printed Inconel 718 (IN718) is a strong alternative to forged components, especially considering the printable dimensions. While the mechanical properties of IN718 are slightly lower than those of forged parts, they are superior to those of cast components [70]. In the case of Ti-6Al-4V applied to impellers, research indicates that residual deformation can be reduced by 20.19% compared to solid compressor impellers, and the residual stress in lattice impellers is lower than in solid ones, with a reduction in the maximum residual stress by 8.72% [71,72]. Additionally, studies on thermal deformation show that the maximum deformation in 3D-printed turbines typically occurs at the base edge [73]. In another case, samples printed using Al-Si-Mg material exhibited a hardness 35% higher than that of the cast alloy [74].

Austenitic steel printing shows that, with a new design, the impellers can operate at higher rotational speeds ranging between 8.2% and 32.73% at an inlet pressure of 5 MPa and different nozzle angles in applications to Pelton turbines [75]. In martensitic steel printing, the rotational speed has a linear influence on the critical crack size and a nonlinear influence on the fatigue crack propagation life. When the external load and the residual stress of 3D printing act at the same time, the crack propagation law is no longer complied with [76]. Martensitic steel shows changes in pore size and difficulty in repeatability of results, but there is no variation in total porosity. The applied heat treatment (solution and aging hardening) showed superior performance and improved tensile strength [77].

The SLM printing process allows the fabrication of high-precision geometries, ensuring imposed constraints [78]. Regarding post-processing operations, results show improvements in surface quality through Abrasive Flow Machining (AFM) [66]. With AlSi10Mg material, it is observed that the component manufactured through SLM has a better surface finish compared to the cast component and meets the impeller specification requirements [74]. Regarding the production of smaller-sized impellers in the future, the results show that the impeller can not only effectively reduce weight [79] but also improve compressor efficiency [80].

In unconventional applications, the material FeSiCr, considered a Soft Magnetic Composite (SMC), is an applicable option for high-efficiency axial flow machines, high-speed airflow, and power density. With this manufacturing method, a 3D-structured motor with high structural strength and low core loss during high-frequency operation could be rapidly fabricated [81]. On the other hand, impellers for cryogenic pumps have also been developed, obtaining improved mechanical properties compared to standard impellers [82].

Regarding new processes, the construction of ceramic cores through selective laser sintering (SLS) was evidenced. Additionally, the organic-inorganic binder conversion process was used to increase the mechanical properties of the prepared core. Ref. [83] used mullite powder with a size of 70 μm and phenolic organic resin as the starting material; the casting of the impeller blade was successful, and the product precision was high in a real application. The ceramics obtained by selective laser sintering (SiC-Si(BN)-Al_2O_3), followed by heat treatment, are three to five times less massive than metallic ones and sufficiently compact for applications such as building materials for the production of microturbines [84]. With polystyrene (PS) after the T5 heat treatment, the tensile strength and Brinell hardness of the cast part increase from 184 MPa and 57 HB to 330 MPa and 109 HB, respectively [85]. Similarly, this technology has been applied with turboexpanders using Nylon [86]. There is also evidence of good performance in closed impellers with stainless steel SS304 [87].

Ceramic Gas Microturbines (μGTU-MTG) produced by SLS technology have enabled increased efficiency, power density, elimination of toxic component emissions from the exhaust, significant reduction in mass and dimensional characteristics, ensuring continuous optimum performance, increasing reliability, and reducing costs and operating costs [84,88]. MTGs have been fabricated in Inconel, but the geometric profiles and finishes are not suitable [89].

Another process used is MJF, which is capable of controlling different properties in its voxels, allowing for the obtaining different mechanical characterizations, different colors, and transparency in the same product. According to [90], when printing parts of a stator, the MJF process turned out to be a reasonable solution in Polyamide, but it is only viable if more exhaustive preliminary tests are carried out. Another study shows that some components in a fan were deformed during the cooling process, generating non-precise tolerances. In addition, only a few materials were allowed in MJF, such as PA 12 or PA11 [91]. Although it is possible to produce elements with suitable geometries and dimensions using this technology, they have microstructural problems, such as porosity between layers or unprocessed powder particles in the printing structure [92].

The Electron Beam Melting (EBM) process can work with materials of superior properties. According to [93], EBM is highly suitable for constructing circular or complex shapes with thin walls. EBM can produce parts with an approximate relative density of 98% in TiAl components, whereas, compared to SLM, the produced parts exhibit poorer mechanical properties and a relative density of 97% due to cracks [94]. This method can also be used to repair parts. When a part is worn or exceeds its anticipated lifespan, it can be cut, designed, and a new feature built onto the existing part [93,95]. In the manufacturing of impellers in Ti-6Al-4V, a decrease in mechanical properties during production due to prolonged annealing has been observed [96], although studies by [97] mention that surface treatments can significantly enhance the quality and reliability of the parts.

For small-scale and low-load applications, Stereolithography (SLA) can prove to be a valuable ally. This method has been tested with resin and polymers on impellers, mostly using Acrylonitrile Butadiene Styrene (ABS). The SLA method applied to turboexpanders with resin results in a glass-like surface with a fine finish, though its fragility poses a problem in practical applications [86]. There are experimental tests in photopolymer demonstrating the possibility for rapid and low-cost construction of rotary compressors, although there are no tests for general characterization [98]. ABS material is capable of producing a significant amount of thrust at extremely low RPMs compared to standard propeller systems in medical applications [99]. Combined applications with casting have also been found, where the wax pattern is generated in high-impact polystyrene (HIPS) using SLS and photosensitive resin using SLA. There are few studies related to turbines used in low RPM and small-scale applications [100].

Furthermore, Digital Light Processing (DLP) technology has proven that it is possible to manufacture a cost-effective ceramic turbine through a turbine rotor with alumina and silicon nitride [101]. Ref. [102] successfully manufactured a complex-shaped silicon nitride impeller suitable for transporting molten mass at high temperatures using this technology. Additionally, Ref. [89] manufactured a ceramic-type Si-Al-O-N rotor under this technology, demonstrating superior efficiency and pressure ratio compared to rotors made with SLS technology and Inconel material due to better geometric features and superior surface finish.

Ref. [103] shows that it is possible to use photopolymers in the manufacturing of impellers, but their operation is at a lower flow pressure than a standard material impeller, due to the absence of sharp edges, although it is acceptable in quick design solutions. It is also known that DLP can be used to obtain lost wax patterns for subsequent casting, achieving lower costs than traditional manufacturing [104].

Regarding Laser Metal Deposition (LMD) technology, it has been shown that combining LMD with multi-axis milling is a viable solution for the production of closed impellers and other complex-shaped parts [105]. Ref. [106] mentions that the cost of components compared to the conventional casting process is slightly higher, and the significant reduction in delivery time can be the deciding factor when parts are needed quickly. In terms of costs, Ref. [107] has proposed an experimental method achieving lower power consumption, higher decomposition performance, and printing efficiency compared to the traditional method. There is not much evidence of the use of this technology on a large scale in turbomachinery, according to the state of the art.

Polyjet technology, on the other hand, allows the design of composite components from different polymeric materials and even medical products or applications [108]. Regarding impellers, Polyjet technology has been used for experiments and evaluations of impeller wear by sludge using VeroGray material, allowing rapid assessment of wear locations and rates in harder materials [109]. In small-scale applications for solar radial turbines, RG525 material was used for experimentation; the maximum allowable deformation was influenced by the rotation speed, the maximum allowable fatigue life was influenced by the rotation speed and the fluid intake temperature, and the tip cover region on the rotor had deflection values greater than 21% [95,110]. In Polycarbonate (PC) material, the hydraulic performance could match the commercial product when manufacturing a monopivot centrifugal blood pump [111]. This additive manufacturing application has enabled functional solutions in renewable energy applications. In applications to small Pelton turbines, two variants were designed: screw-on rotor buckets and a monoblock rotor turbine, allowing for complex designs and customized solutions [112].

Regarding the Fused Deposition Modeling (FDM) process, there are various applications related to turbomachinery offering advantages and disadvantages. In materials such as ABS and Polyactide (PLA), it is evident that costs can be reduced, but there are limitations such as the production of large components and damage in post-processing [113]. In other applications, the use of a large number of support structures leads to high post-production costs [78,114]. It is known that the main disadvantage of filament printers is the formation of gaps when printing intricately shaped objects [115]. In contrast to the above, a mixed process (3D printing and rapid lost wax casting) in centrifugal compressors, processing time and costs were reduced, and casting quality improved [116]. The use of Polyurethane (PU) in impellers for floaters is considerably economical and increases the production process of new parts [117].

In terms of performance [118], it was demonstrated that a pump designed with Polyethylene Terephthalate Glycol-Carbon Filament (PETG-CF) has an efficiency of 26.23%, comparable to a tin-bronze impeller, which has an efficiency of 27.7% in hydrophore pumps. On the other hand, [119] shows that impellers in PLA at speeds not exceeding 1000 rad/s or pressures below 0.22 MPa could operate without compromising their efficiency and structural integrity. The performance characteristics of ABS-P430 pump impellers have similar functional values and very identical trends of the functional curves of total height, energy consumption, and mechanical efficiency [120]. Ref. [121] evidences that among five impeller variants with the same flow section geometry and similar material (ABS-P430), the impellers produced by 3D printing showed slightly higher efficiency compared to cast iron and steel impellers, averaging between 4 and 6%.

Bound Metal Deposition (BMD) currently has limited applications in turbomachinery [122]. Despite this, there are examples of applications in impellers, such as the centrifugal pump impeller printed from SS 316L using BMD. Another clear example is the pump impeller made of SS 316L material, showing similar properties compared to a CNC-machined SS 316L impeller [123].

Binder Jetting Printing (BJP) technology also has few applications in turbomachinery. In another study, the design of an actual impeller blade was successful, and the product precision was excellent [83]. It was discovered that the BJP process prints elements more economically and 20% more resistant than those processed by other additive manufacturing techniques [124]. When comparing SLS printing with BJP, the former offers the advantage of the efficiency of inorganic binder coating, for example, furan [83].

3.3. III. Data Analysis

Regarding manufacturing processes and materials, common subtractive processes such as CNC have been used to design high-performance centrifugal compressors using 2014-T6 aluminum alloy as the manufacturing material [125]. Similarly, materials used for high-performance centrifugal impellers are those with a higher yield strength and minimal specific weight, such as ASTM A3, Hardox 450, and 6061-T6 [126].

In the realm of additive manufacturing, there are ongoing studies and continuous improvements in printable materials. For example, Ref. [127] designed an enhanced agitation impeller printed in polylactic acid (PLA), which was then doped with iron as a raw material to subsequently generate chemical activity through surface etching and oxidation [87]. In an effort to design corrosion-resistant elements, materials used in centrifugal pumps such as cast iron and brass alloy versus polymeric materials like polyamide 6 reinforced with 15% carbon fiber (PA6-CF15) and 15% polyphenylene sulfide reinforced with carbon fiber (PPS-CF15) have been evaluated. Composite materials were suitable for operating at nominal impeller powers but did not withstand the maximum load that metallic materials can bear. The printed impellers were demonstrated to be free of corrosion or related phenomena such as wear, erosion, and fatigue. A low water absorption rate and chemical resistance were also evident [128]. Notably, experimental studies have aided in finding improvements in materials and applications related to turbomachinery.

From the review, various materials used in impellers across different additive manufacturing techniques were observed, as shown in Table 2, with AISI316L, Al_2O_3, Inconel, and Ti-6Al-4V being the most used in metals. It was evidenced that AISI316L is one of the most utilized materials across various processes (LMD, BMD, BJP, DMLS-LPBF-SLM) and is highly used in impellers due to its high mechanical strength, corrosion and wear resistance, longevity, high-temperature resistance, ease of maintenance, and good performance at low temperatures [129,130]. Al_2O_3 is used in ceramic components, rotors, microturbines, ceramic cores, or matrices [84]. Inconel is a difficult-to-machine material used in components subjected to high temperatures and corrosion resistance. It is currently handled by aerospace, oil, gas, nuclear, and chemical industries [131]. Although AM exhibits slightly lower mechanical properties than forged parts [132,133], this process resolves many machining issues. Ti-6Al-4V is another material highly used in AM for its high strength, low density, corrosion resistance, biocompatibility, and high-temperature resistance, although it presents porosity issues, heat treatments, and pressing are performed to correct them [134].

Table 2. Common materials in impellers used in additive manufacturing.

Process	Material	References
SLS	SS 304 (HIPS-Stainlees steel), SiC-Si (BN)-Al_2O_3, Mullite ($3Al_2O_3 \cdot 2SiO_2$), PS, Nylon	[83–86,88,135]
SLA	ABS, Resina	[86,99]
DLP	Si_3N_4, Photopolymer, Al_2O_3, Si_3N_5	[101–103]
LMD	AISI316L	[136]
MJF	PA12GB (Nylon y 40% vidrio)	[90]
Polyjet	PC, FullCure 720 (Clear Resin), RGD 525 (Stratasys material), VeroGray	[109–112]
FDM	ABS-P430, PLA, ABS, PU, Polycast, PET, PLA, PA6-CF15, PPS-CF15, ABS, PETG CF	[78,86,113,115–121,128]
BMD–BJP	AISI316L, Quartz (SiO_2)	[83,123]
EBM	Ti-6Al-4V	[93,96]
DMLS-LPBF-SLM	AlSi10Mg, 17-4 PH Stainless Steel, Ti-6Al-4V, Inconel 718, Inconel 625, AISI316L, FV520B-I, FeSiCr Martensitic Steel, SUS316L	[66–73,75–82,86,137]

For applications in turbomachinery, particularly impellers operating in corrosive fluid environments, it is crucial to select materials with high corrosion resistance, classified under Corrosion Resistance Classes CRC (CRC3 and CRC4), to ensure durability and performance in such environments. Materials such as Inconel 718, Inconel 625, Ti-6Al-4V (Titanium), and Si_3N_4 (Silicon Nitride) are excellent choices for additive manufacturing due to their high corrosion resistance and ability to withstand extreme conditions. Studies show that corrosion can impact the performance of critical components and can form depletion zones in various elements [138]. Materials like alumina (Al_2O_3) can mitigate the effects of erosion and high-temperature corrosion, or remanufacturing processes and coatings with nickel alloys can enhance corrosion resistance [139,140]. Although many materials exhibit good qualities by being stainless, AM alloys may be affected by heat and can contain residual stresses created by the manufacturing process itself [139]. Table 3 shows the materials used in additive manufacturing and their corrosion resistance in various environments.

Table 3. Corrosion resistance of materials used with AM in impellers.

Material	Mils per Year—mpy	Corrosion Resistance	CRCI [1]	CRC [2]
SS 304 (HIPS-Stainless Steel)	2–20 mpy (in seawater)	Medium	0.75–1.0	CRC2
SiC-Si (BN)-Al_2O_3, Mullite	<0.1 mpy	High	>1.0	CRC3
PS (Polystyrene)	Low resistance, not used in corrosive environments	Low	-	CRC1
Nylon	0.1–1 mpy (in diluted acids)	Low	0.8–0.9	CRC2
ABS	1–10 mpy (depending on the medium)	Low	0.6–0.8	CRC1
Resin	Depends on type, generally low	Low	0.5–0.7	CRC2
Si_3N_4 (Silicon Nitride)	<0.1 mpy	High	>1.0	CRC4
Photopolymer	Depends on type, generally low	Low	0.4–0.7	CRC2
Al_2O_3 (Aluminum Oxide)	<0.1 mpy	High	>1.0	CRC3
Si_3N_5	<0.1 mpy	High	>1.0	CRC4
AISI316L (Stainless Steel)	0.5–5 mpy (in seawater)	High	0.9–1.0	CRC3
PA12GB (Nylon and 40% glass)	Similar to Nylon, 0.1–1 mpy	Low	0.8–0.9	CRC2
PC (Polycarbonate)	1–10 mpy	Low	0.7–0.9	CRC2
FullCure 720 (Clear Resin)	-	Low	-	CRC2
RGD 525 (Stratasys material)	-	Low	-	CRC2
VeroGray	-	Low	-	CRC2
ABS-P430	Similar to ABS, 1–10 mpy	Low	0.6–0.8	CRC1

Table 3. *Cont.*

Material	Mils per Year—mpy	Corrosion Resistance	CRCI [1]	CRC [2]
PLA	1–10 mpy (depending on the medium)	Low	0.6–0.8	CRC1
PU (Polyurethane)	1–10 mpy	Low	0.6–0.8	CRC2
Polycast	Similar to ABS	Low	0.6–0.8	CRC2
PET	1–10 mpy (depending on the medium)	Low	0.7–0.9	CRC2
PA6-CF15	Similar to PA6, 1–10 mpy	Low	0.7–0.9	CRC2
PPS-CF15	<0.1 mpy (in acidic media)	Low	0.9–1.0	CRC3
PETG CF	Similar to PET, 1–10 mpy	Low	0.7–0.9	CRC2
Quartz (SiO_2)	<0.1 mpy	High	>1.0	CRC4
Ti-6Al-4V (Titanium)	<0.1 mpy (in seawater)	High	>1.0	CRC4
AlSi10Mg (Aluminum Alloy)	1–5 mpy (in saline environments)	Medium	0.8–0.9	CRC2
17-4 PH Stainless Steel	0.5–5 mpy (in seawater)	High	0.9–1.0	CRC3
Inconel 718	<0.1 mpy (in acidic or saline environments)	Very High	>1.0	CRC4
Inconel 625	<0.1 mpy (in acidic or saline environments)	Very High	>1.0	CRC4
FV520B-I	1–10 mpy	Medium	0.8–0.9	CRC3
FeSiCr (Iron-Silicon-Chromium Alloy)	<0.1 mpy	High	>1.0	CRC3
Martensitic Steel	5–20 mpy (in saline environments)	Medium	0.6–0.8	CRC2
SUS316L (Stainless Steel)	0.5–5 mpy (in seawater)	High	0.9–1.0	CRC3

[1] Corrosion Resistance Cost Index (CRCI); [2] Corrosion Resistance Classes (CRC).

Despite being more costly, the DMLS-LPBF-SLM processes use materials with higher resistance capabilities and can work with superalloys [141]. This method is increasing in use as it can surpass the limitations of conventional machining and can develop complex shapes, new designs, and optimize various parameters [142]. FDM technology is highly utilized for being more accessible, affordable, capable of generating complex geometries, and exhibiting low corrosion [143]. It may present issues with low precision and post-processing costs [144], and is limited by the materials used (polymers) and the final quality of the part [145], although there is evidence of centrifugal compressors constructed from FDM in Ti-6Al-4V material [146]. Figure 8 briefly indicates the materials commonly used in different types of turbomachinery through FDM.

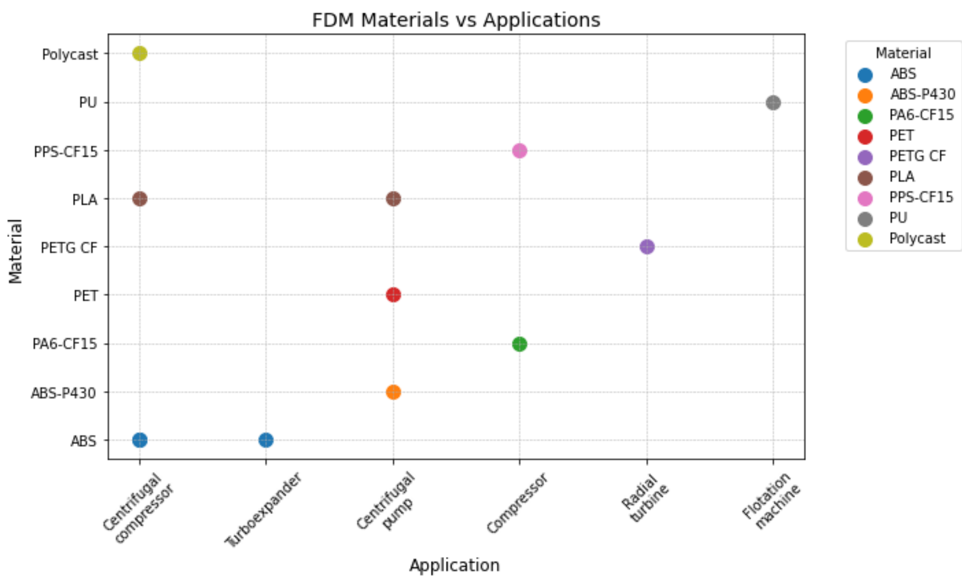

Figure 8. Use of material in FDM in turbomachinery.

Those materials, such as ABS and PLA, are versatile materials used in different types of turbomachinery, like centrifugal compressors, turboexpanders, and centrifugal pumps. Materials like PU and PETG CF are associated with specific applications such as flotation machines and radial turbines, respectively. The concentration of applications is commonly found in compressors and centrifugal pumps.

Regarding the relationship between speed and material, it is known that the value of the stress gradually increases as the speeds of the impeller increase; thus, mechanical properties are influential in the design of turbomachinery [147]. Another important point is related to wear, since accelerated wear in impellers directly affects hydraulic power [148]. Regarding the surface, reducing the roughness of the impeller positively affects the efficiency of the pump and energy requirements, although flow handling tends to be lower with polymeric materials [149]. Ceramic materials like Al_2O_3, Si_3N_5, and metallic materials such as Ti6Al4V printed in 3D have shown good results at high revolutions (Figure 9). Although polymeric materials are not suitable for high-revolution work, in demonstrated applications, they have improved performance parameters, costs, and sustainability [150].

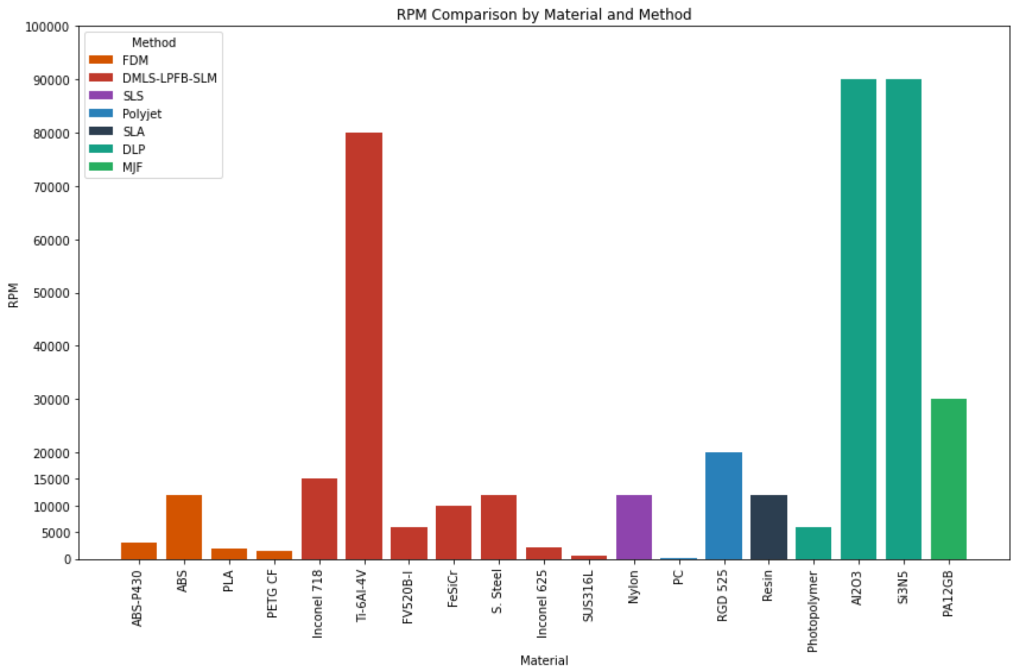

Figure 9. Tested speeds of 3D-printed impellers.

AM compressors could provide significant improvements in cost and weight of the engine for limited-life applications [151]. The introduction of additive manufacturing technologies combined with other standard manufacturing methodologies could yield reasonable benefits regarding production time and component availability. For example, the use of simulation elements, numerical control methods, algorithms, and additive manufacturing, among others, can allow significant advancements in the design and optimization of elements in turbomachinery [152,153]. Table 4 shows some materials, methods, applications, and speeds at which certain materials have been studied, obtaining notable advantages.

Additive manufacturing (AM) has emerged as a versatile and innovative approach for producing turbomachinery components. Different AM techniques, such as DMLS/SLM, SLS, and EBM, offer unique advantages in terms of material optimization, design flexibility, and sustainability. Table 5 summarizes the advantages, disadvantages, and key mechanical/physical defects of various additive manufacturing (AM) techniques applied in turbomachinery.

Table 4. Materials, methods, applications, and speeds applied to turbomachinery related to additive manufacturing.

Material	Method	Application	RPM
PEEK	CNC–3D	High Speed Microturbine	120,000
PPS	CNC–3D	High Speed Microturbine	120,000
Aluminum 2014-T6	Ansys CFD Simulation	Centrifugal Compressor	230,000
ASTM A36	Ansys CFD Simulation	Fan	653
Hardox 450	Ansys CFD Simulation	Fan	1225
Aluminum 6061-T6	Ansys CFD Simulation	Fan	1002
ABS-P430	FDM	Generator	2950
Aluminum 2014-T6	Ansys CFD Simulation	Compressor	210,000
Inconel 718	DMLS-LPFB-SLM	Centrifugal Compressor	14,700
Inconel 718	DMLS-LPFB-SLM	Centrifugal Compressor	15,120
ABS	FDM	Centrifugal Compressor	2800
ABS-P430	FDM	Centrifugal Pump	1450
Ti-6Al-4V	DMLS-LPFB-SLM	Compressor	80,000
FV520B-I	DMLS-LPFB-SLM	Compressor	6000
FeSiCr	DMLS-LPFB-SLM	Fan	10,000
PLA	FDM	Centrifugal Pump	1900
Nylon	SLS	Turboexpander	12,000
ABS	FDM	Turboexpander	12,000
Stainless steel	DMLS-LPFB-SLM	Turboexpander	12,000
PC	Polyjet	Centrifugal Blood Pump	50
Resin	SLA	Turboexpander	12,000
Inconel 625	DMLS-LPFB-SLM	Compressor	2200
RGD 525	Polyjet	Radial Turbine	20,000
PETG CF	FDM	Radial Turbine	1450
SUS316L	DMLS-LPFB-SLM	Pelton Turbine	500
Ti-6Al-4V	DMLS-LPFB-SLM	Compressor	570
Photopolymer	DLP	Centrifugal Pump	5900
Al_2O_3	DLP	Turbine Rotor	90,000
Si_3N_5	DLP	Turbine Rotor	90,000
PA12GB	MJF	Radial Turbine	30,000

AM in turbomachinery offers significant benefits in terms of sustainability, notably optimizing material usage, energy consumption, and production times. Processes such as DMLS-LPBF-SLM have demonstrated substantial weight reductions in components, achieving nearly a 30% decrease in the total mass of impellers manufactured from Inconel 718 while also optimizing operational frequencies [69]. In materials such as AISI316L, BMD technology proves eco-efficient, reducing environmental impacts by 54.6% compared to commercial alternatives [123]. For ABS-P430, the FDM process increases efficiency by 4–6% [121], while PETG CF components achieve efficiencies of 26.23%, comparable to those of bronze materials [118]. Additionally, processes like SLS reduce production costs, with lead times of approximately two weeks compared to 40–50 weeks for traditional methods [135]. In terms of repair and reuse, EBM enables the restoration of worn or out-of-service components, enhancing sustainability by extending their operational lifespan [96]. Furthermore, technologies such as DLP, applied to ceramic materials like Si3N4, meet the demands of high-temperature and molten transfer applications, expanding the possibilities of sustainable manufacturing [102]. Finally, advanced methods, such as those implemented by [81], facilitate the production of 3D motors with high structural strength and minimal core loss, emphasizing the energy efficiency and operational performance of these technologies.

Despite the advancements in AM, key sustainability challenges remain. Processes such as SLM exhibit porosity and structural defects, which affect component durability [91,92]. Similarly, EBM technologies face high energy consumption during production and significant material recovery costs in post-processing [94,96]. Methods like FDM generate considerable waste due to support structures, increasing costs and material losses [114]. Moreover, the reuse of sintered powder in technologies such as SLS and the scalability of processes like BMD for industrial applications remain critical areas for improvement [83,124]. Studies also indicate the need to assess the full life-cycle impact of advanced materials used in Polyjet [71,103]. These limitations highlight the necessity for innovation to achieve truly sustainable AM or to apply recent findings to impeller production. For example, studies on the use of Inconel 625 via wire arc additive manufacturing (WAAM) have shown a threefold reduction in energy consumption and a material waste reduction from 85% to 35% [154].

Table 5. Advantages, disadvantages, and mechanical/physical defects of AM techniques.

AM Technique	Advantages	Disadvantages	Mechanical/Physical Defects
DMLS-LPBF-SLM	High dimensional accuracy, excellent material strength, up to 30% weight reduction, and optimized operational frequencies.	Residual stresses, porosity, lack of fusion, thermal deformation, and high costs.	Residual stresses, porosity, thermal deformation, surface roughness, and lack of fusion.
SLS	Significant cost reductions (up to 99.75%), short production times, lighter and more efficient components.	Low density, high surface roughness, and limited material options.	Low density, high surface roughness, and deformation during cooling.
EBM	Capable of producing and repairing complex components, high mechanical strength, and relative density of 98%.	High energy consumption, susceptibility to cracking in materials such as Ti-6Al-4V.	Cracking in thin components and loss of properties due to prolonged annealing times.
FDM	Cost-effective, efficient for complex geometries, improves performance by 4–6% in materials such as ABS and PETG CF.	Formation of voids, layer adhesion issues, and limitations for high-speed or high-temperature applications.	Delamination between layers, void formation, limited precision, and excessive waste from support structures.
DLP	Excellent surface finish, suitable for high-temperature applications using ceramics such as Si3N4.	Material fragility, limited material compatibility, and flow and pressure challenges.	Material fragility, flow and pressure issues, and limited mechanical strength.
BMD	Highly eco-efficient, reducing environmental impacts by 54.6% compared to conventional methods.	Scalability issues for industrial applications and material density inconsistencies.	Difficulty in achieving repeatability, interlayer porosity, and limited mechanical strength in complex shapes.
MJF	Allows precise control of voxel-specific properties, high resolution, and functional prototypes.	Material restrictions, deformation during cooling, and interlayer porosity.	Interlayer porosity, unprocessed powder particles, and variability in dimensional tolerances.
SLA	Ideal for low-load applications, fast and cost-efficient for rotary compressors using ABS and photosensitive resins.	Fragile parts, roughness in vitreous surfaces, and limited mechanical strength.	Fragility, high roughness on vitreous surfaces, and unsuitability for high-load or high-speed components.
PolyJet	Capable of producing multi-material components, ideal for wear testing, and small-scale energy applications.	Material compatibility limitations, deformation in high-stress conditions, and restricted scalability.	Deformation in high-rotation speed conditions, wear inconsistencies in testing materials.
LMD	Viable for producing closed impellers and other complex shapes, reduces powder consumption, and improves decomposition efficiency.	Higher cost compared to traditional casting processes, limited evidence of large-scale adoption in turbomachinery.	Porosity in deposited layers, residual stresses, and inconsistencies in mechanical properties.

At the policy level, it is crucial to establish financial incentives to support research and industrial implementation of additive manufacturing in turbomachinery, alongside specific regulations to ensure quality and sustainability. Encouraging public-private partnerships is essential to address technical and environmental challenges effectively. Additionally, conducting comprehensive life cycle assessments, providing technical training to professionals in these technologies, and promoting the use of locally sourced materials are fundamental steps to tailor solutions to regional contexts and enhance their practical applicability.

4. Conclusions

A co-occurrence analysis was performed, and it was determined that the number of studies is relatively low, considering that scientific interest, according to publications, has intensified since 2016. It is notable that the areas of interest are related to topics such as topological optimization, simulation, material alloying, performance improvement, and the repair of turbomachinery components.

From the analyzed study, FDM printing and powder bed fusion technology are the most widely used in this field. The advantages and disadvantages of AM depend mainly on the type of process, the material used, post-processing, and its application. For example, the DMLS process produces impellers with adequate dimensional accuracy, surface finish, and good strength in materials such as 17-4 PH, Ti-6Al-4V, Inconel 625, and Inconel 71,800. The hardness of the Al-Si-Mg material produced by this method is 35% higher than that of the cast alloy. In contrast, the SLS process with MTGs printed in Inconel results in inadequate geometric profiles and finishes. Similarly, the results obtained from FDM demonstrate that it is possible to reduce costs and improve performance, but it shows limitations such as the production of large components, load limitations, costs, and damage in post-processing.

In recent years, optimization methods have become more varied, and several techniques have been combined to achieve better results. It is possible to combine manufacturing methods, for instance, using lost wax for casting, resulting in lower costs compared to traditional manufacturing. The same can be done with CNC processes, which offer options for repairing impellers in mixed processes, or by combining various processes to achieve different types of optimizations.

Given the growing scientific interest in 3D printing technologies since 2016, especially in areas like topological optimization, material simulation, material wear, and performance enhancement in turbomachinery, it is clear that additive manufacturing (AM) offers substantial potential for practical applications in pumps. Despite challenges such as size limitations, load capacity, and post-processing costs associated with Fused Deposition Modeling (FDM), the prospects for cost reduction and performance improvement are highly promising. Additionally, integrating AM with traditional manufacturing techniques, such as lost-wax casting or CNC machining, can further enhance process efficiency and cost-effectiveness. This makes the application of 3D-printed materials in pumps not only feasible but also highly advantageous.

This research provides a deeper understanding of the advancements in AM for the production of turbomachinery components, highlighting the use of materials such as Ti-6Al-4V, Inconel 718, and reinforced polymers, which offer enhanced resistance to corrosion, wear, and high temperatures. These developments enable the creation of more complex and optimized geometries, significantly improving the performance and efficiency of impellers and other critical components. Furthermore, the advancements studied establish a solid foundation for mitigating the combined effects of wear, including erosion, cavitation, and corrosion, through the integration of Industry 4.0 digital enablers, such as digital twins and advanced simulations. Future research directions should focus on further optimizing materials, exploring hybrid processes that combine AM with traditional techniques, reducing microstructural defects to enhance component reliability, and advancing algorithms to improve design and operational efficiency in turbomachinery.

Author Contributions: Conceptualization, M.P.-S. and A.R.; methodology, A.R.; formal analysis, F.-J.S.-R. and V.H.H.; investigation, A.R. and M.P.-S.; resources, F.-J.S.-R. and M.P.-S.; writing—original draft preparation, A.R., V.H.H., M.P.-S., H.M.R. and F.-J.S.-R.; writing—review and editing, A.R. and M.P.-S.; supervision, M.P.-S. and V.H.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The used data are available in the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Acronyms

ABS	Acrylonitrile Butadiene Styrene
AFM	Abrasive Flow Machining
AM	Additive Manufacturing
BJP	Binder Jetting Printing
BMD	Bound Metal Deposition
CNC	Computed Numeric Control
CRC	Corrosion Resistance Classes
CRCI	Corrosion Resistance Cost Index
DLP	Digital Light Processing
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
FDM	Fused Deposition Modeling
HIPS	High-Impact Polystyrene
IIoT	Industrial Internet of Things
IN718	Inconel 718
LPBF	Laser Powder Bed Fusion
LMD	Laser Metal Deposition
MJ	MultiJet
MJF	Multi Jet Fusion
MTG	Micro Gas Turbine
PA	Polyamide
PA6-CF15	Polyamide 6 reinforced with 15% carbon fiber
PCMs	Polymeric Composite Materials
PEEK	Polyether-ether-ketone
PET	Polyethylene Terephthalate
PETG	Polyethylene Terephthalate Glycol
PPS	Polyphenylene sulfide
PPS-CF15	Polyphenylene sulfide reinforced with 15% carbon fiber
PU	Polyurethane
SDGs	Sustainable Development Goals
SiC	Silicon Carbide
SLA	Stereolithography
SLM	Selective Laser Melting
SMC	Soft Magnetic Composite
SLS	Selective Laser Sintering
SS	Stainless Steel
WDE	Water Droplet Erosion
sCO_2	Supercritical CO_2
WAAM	Wire Arc Additive Manufacturing

References

1. Lagha, M.; Duplaa, S.; Binder, N.; Carbonneau, X. Unified Classification and Characterization of Axial Turbomachines and Propellers. In Proceedings of the 13th International Symposium on Experimental Computational Aerothermodynamics of Internal Flows, Okinawa, Japan, 7–11 May 2017; p. 1.
2. Singh, A.; Sharma, D. Efficiency Enhancement in Turbomachinery: Bridging Numerical Modeling and Experimental Validation for Fluid Dynamics Advancements. *J. Sustain. Urban Futures* **2023**, *13*, 1–15.
3. Srinivas, G.; Raghunandana, K.; Shenoy, B.S. Recent Developments in Turbomachinery Component Materials and Manufacturing Challenges for Aero Engine Applications. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Melbourne, Australia, 15–16 September 2018; IOP Publishing: Bristol, UK, 2018; Volume 314, p. 012012.
4. Patel, M.; Kumar, A.; Pardhi, B.; Pal, M. Abrasive, Erosive and Corrosive Wear in Slurry Pumps—A Review. *Int. Res. J. Eng. Technol.* **2020**, *7*, 2188–2195.
5. Yonezawa, K.; Nakai, G.; Takayasu, M.; Sugiyama, K.; Sugita, K.; Umezawa, S.; Ohmori, S. Influence of Blade Corrosion on Aerodynamic Characteristics of a Gas Turbine. *Energy* **2021**, *230*, 120665. [CrossRef]
6. Linden, D. Know Your Turbomachinery's Operating Environment! In Proceedings of the 47th Turbomachinery Symposium, Houston, TX, USA, 18–20 September 2018; Turbomachinery Laboratory, Texas A&M Engineering Experiment Station: College Station, TX, USA, 2018.

7. Yang, S.; Gao, S.; Xue, W.; Wu, B.; Duan, D. Phenomenological Modeling of Wear Mechanisms between Nickel-Based Superalloy Blades and Ceramic-Based Abradable Coatings in Turbomachines. *J. Mater. Res. Technol.* **2023**, *27*, 4191–4203. [CrossRef]
8. Di, J.; Wang, S.; Yan, X.; Cai, L.; Xie, Y. Experimental Investigation on Effect of Surface Strengthening Process and Roughness on Water Droplet Erosion Behavior in Turbomachinery. *Tribol. Int.* **2021**, *153*, 106647. [CrossRef]
9. Torner, B.; Wurm, F.-H. Influence of Zonal Surface Roughness on the Pump Characteristics of a Turbopump. In Proceedings of the 15th European Conference on Turbomachinery Fluid dynamics & Thermodynamics, Budapest, Hungary, 24–28 April 2023; European Turbomachinery Society: Florence, Italy, 2023.
10. Alqallaf, J.; Teixeira, J.A. Blade Roughness Effects on Compressor and Engine Performance—A CFD and Thermodynamic Study. *Aerospace* **2021**, *8*, 330. [CrossRef]
11. Radgolchin, M.; Anbarsooz, M. Fatigue Failure of Centrifugal Compressor Impellers: A Comprehensive Review. *Eng. Fail. Anal.* **2023**, *153*, 107592. [CrossRef]
12. Doshi, S.; Katoch, A.; Suresh, A.; Razak, F.A.; Datta, S.; Madhavan, S.; Zanhar, C.M.; Gundabattini, E. A Review on Vibrations in Various Turbomachines Such as Fans, Compressors, Turbines and Pumps. *J. Vib. Eng. Technol.* **2021**, *9*, 1557–1575. [CrossRef]
13. Wang, Y.; Liu, T.; Meng, Y.; Zhang, D.; Xie, Y. Integrated Optimization for Design and Operation of Turbomachinery in a Solar-Based Brayton Cycle Based on Deep Learning Techniques. *Energy* **2022**, *252*, 123980. [CrossRef]
14. Gou, L.; Zeng, X.; Wang, Z.; Han, G.; Lin, C.; Cheng, X. A Linearization Model of Turbofan Engine for Intelligent Analysis towards Industrial Internet of Things. *IEEE Access* **2019**, *7*, 145313–145323. [CrossRef]
15. Xie, R.; Chen, M.; Liu, W.; Jian, H.; Shi, Y. Digital Twin Technologies for Turbomachinery in a Life Cycle Perspective: A Review. *Sustainability* **2021**, *13*, 2495. [CrossRef]
16. Brun, K. Turbomachinery for Carbon Dioxide Transport and Storage. In *Offshore Technology Conference*; OTC: Hollister, MO, USA, 2023; p. D011S010R001.
17. Cetin, T.H.; Zhu, J. Aerodynamic Design and Optimization of SCO2 Turbomachinery: Two-Stage Optimization Approach. *Energy Convers. Manag.* **2023**, *297*, 117711. [CrossRef]
18. Reddy, T.R.; Priyadarsini, C.I.; Navaneetha, R. Design and Analysis of Impeller Using Corrosion Resistant Materials. In *AIP Conference Proceedings*; AIP Publishing: Melville, NY, USA, 2021; Volume 2317.
19. Wang, Y.; Li, W.; He, T.; Liu, H.; Han, C.; Zhu, Z. Experimental Study on the Influence of Particle Diameter, Mass Concentration, and Impeller Material on the Wear Performance of Solid–Liquid Two-Phase Centrifugal Pump Blade. *Front. Energy Res.* **2022**, *10*, 893385. [CrossRef]
20. Bandi, S.; Banka, J.; Kumar, A.; Rai, A.K. Effects of Sediment Properties on Abrasive Erosion of a Centrifugal Pump. *Chem. Eng. Sci.* **2023**, *277*, 118873. [CrossRef]
21. Shen, Z.; Chu, W.; Li, X.; Dong, W. Sediment Erosion in the Impeller of a Double-Suction Centrifugal Pump—A Case Study of the Jingtai Yellow River Irrigation Project, China. *Wear* **2019**, *422–423*, 269–279. [CrossRef]
22. Mirmahdi, E. Defects in Turbine Impeller Blades with Non-Destructive Testing: Modeling, Ultrasonic Waves, Defect Analysis. *J. Inst. Eng. (India) Ser. C* **2021**, *102*, 1395–1401. [CrossRef]
23. Li, X.; Zeng, X.; Zhao, Z.; Zhang, X.; Yan, Q.; Zhang, Y.; Wen, Y.; Yang, X.; Mao, F. Fast-flowing LBE Corrosion of the SiC Pump Impeller: Numerical and Experimental Investigations. *Int. J. Appl. Ceram. Technol.* **2023**, *20*, 436–450. [CrossRef]
24. ElJersifi, A.; Chbihi, A.; Semlal, N.; Bouaouine, H.; Naamane, S. Failure Analysis of a High Chromium Carbon Steel Impeller Operating in Phosphoric Acid Slurry. *Wear* **2021**, *476*, 203660. [CrossRef]
25. Li, L.; Ren, Y.; Chang, S.; Li, M.; Lin, S.; Wang, M. Evaluation of the ATI 718Plus Repaired by Laser Metal Deposition under Heat Treatment Regimes: Microstructures, Mechanical Properties, and Their Heterogeneity. *Mater. Sci. Eng. A* **2023**, *885*, 145540. [CrossRef]
26. Kan, K.; Binama, M.; Chen, H.; Zheng, Y.; Zhou, D.; Su, W.; Muhirwa, A. Pump as Turbine Cavitation Performance for Both Conventional and Reverse Operating Modes: A Review. *Renew. Sustain. Energy Rev.* **2022**, *168*, 112786. [CrossRef]
27. Zhu, D.; Xiao, R.; Liu, W. Influence of Leading-Edge Cavitation on Impeller Blade Axial Force in the Pump Mode of Reversible Pump-Turbine. *Renew. Energy* **2021**, *163*, 939–949. [CrossRef]
28. Zhang, F.; Tao, R.; Zhu, D.; Wu, Y.; Jin, F.; Xiao, R. Anti-Cavitation Leading-Edge Profile Design of Centrifugal Pump Impeller Blade Based on Genetic Algorithm and Decision Tree. *J. Braz. Soc. Mech. Sci. Eng.* **2022**, *44*, 279. [CrossRef]
29. Fei, Z.; Zhang, R.; Xu, H.; Feng, J.; Mu, T.; Chen, Y. Energy Performance and Flow Characteristics of a Slanted Axial-Flow Pump under Cavitation Conditions. *Phys. Fluids* **2022**, *34*, 035121. [CrossRef]
30. Pokharel, N.; Ghimire, A.; Thapa, B.; Thapa, B.S. Wear in Centrifugal Pumps with Causes, Effects and Remedies: A Review. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1037*, 012042. [CrossRef]
31. Li, W.; Li, S.; Ji, L.; Zhao, X.; Shi, W.; Agarwal, R.K.; Awais, M.; Yang, Y. A Study on the Cavitation and Pressure Pulsation Characteristics in the Impeller of an LNG Submerged Pump. *Machines* **2021**, *10*, 14. [CrossRef]
32. Kelley, C.R.; Lopp, G.K.; Kauffman, J.L. Optimizing Piezoelectric Material Location and Size for Multiple-Mode Vibration Reduction of Turbomachinery Blades. *J. Vib. Acoust.* **2021**, *143*, 021007. [CrossRef]
33. Jia, X.Q.; Li, S.Y.; Miu, H.J.; Yang, T.; Rao, K.; Wu, D.Y.; Cui, B.L.; Ou, J.L.; Zhu, Z.C. Carbon Nanomaterials: A New Sustainable Solution to Reduce the Emerging Environmental Pollution of Turbomachinery Noise and Vibration. *Front. Chem.* **2020**, *8*, 683. [CrossRef]

34. Nie, D.; Chen, X.; Wu, Q.; Liu, Y. Stress Corrosion Cracking Behaviors of FV520B Stainless Steel Used in a Failed Compressor Impeller. *Eng. Fail. Anal.* **2020**, *116*, 104701. [CrossRef]
35. Fitriyana, D.F.; Anis, S.; Al Qudus, A.R.; Lakuy, M.A.N.; Ismail, R.; Nugroho, S.; Haryadi, G.D.; Bayuseno, A.P.; Siregar, J.P. The Effect of Post-Heat Treatment on The Mechanical Properties of FeCrBMnSi Coatings Prepared by Twin Wire Arc Spraying (TWAS) Method on Pump Impeller From 304 Stainless Steel. *J. Adv. Res. Fluid Mech. Therm. Sci.* **2022**, *93*, 138–147. [CrossRef]
36. Kyaramyan, K.A.; Nochovnaya, N.A.; Zakharova, N.S.; Kashapov, O.S. Microstructure and Mechanical Properties of the Material and the Surface Residual Stresses of Compressor Impeller Blades Made of a VT41 Titanium Alloy Depending on the Initial State and Incomplete Annealing Conditions. *Russ. Metall. (Met.)* **2021**, *2021*, 1587–1593. [CrossRef]
37. Mamazhonov, M.; Shakirov, B.; Matyakubov, B.; Makhmudov, A. Polymer Materials Used to Reduce Waterjet Wear of Pump Parts. *J. Phys. Conf. Ser.* **2022**, *2176*, 012048. [CrossRef]
38. Zirak, N.; Shirinbayan, M.; Deligant, M.; Tcharkhtchi, A. Toward Polymeric and Polymer Composites Impeller Fabrication. *Polymers* **2021**, *14*, 97. [CrossRef] [PubMed]
39. Soori, M.; Jough, F.K.G.; Dastres, R.; Arezoo, B. Sustainable CNC Machining Operations, a Review. *Sustain. Oper. Comput.* **2024**, *5*, 73–87. [CrossRef]
40. Kantaros, A.; Petrescu, F.I.T.; Brachos, K.; Ganetsos, T.; Petrescu, N. Evaluating Benchtop Additive Manufacturing Processes Considering Latest Enhancements in Operational Factors. *Processes* **2024**, *12*, 2334. [CrossRef]
41. Dalpadulo, E.; Petruccioli, A.; Gherardini, F.; Leali, F. A Review of Automotive Spare-Part Reconstruction Based on Additive Manufacturing. *J. Manuf. Mater. Process.* **2022**, *6*, 133. [CrossRef]
42. Hedayati, R.; Stulova, V. 3D Printing for Space Habitats: Requirements, Challenges, and Recent Advances. *Aerospace* **2023**, *10*, 653. [CrossRef]
43. Hegab, H.; Khanna, N.; Monib, N.; Salem, A. Design for Sustainable Additive Manufacturing: A Review. *Sustain. Mater. Technol.* **2023**, *35*, e00576. [CrossRef]
44. Liu, W.; Liu, X.; Liu, Y.; Wang, J.; Evans, S.; Yang, M. Unpacking Additive Manufacturing Challenges and Opportunities in Moving towards Sustainability: An Exploratory Study. *Sustainability* **2023**, *15*, 3827. [CrossRef]
45. Chyr, G.; DeSimone, J.M. Review of High-Performance Sustainable Polymers in Additive Manufacturing. *Green Chem.* **2023**, *25*, 453–466. [CrossRef]
46. Jiang, J.; Fu, Y.-F. A Short Survey of Sustainable Material Extrusion Additive Manufacturing. *Aust. J. Mech. Eng.* **2023**, *21*, 123–132. [CrossRef]
47. Calignano, F.; Mercurio, V. An Overview of the Impact of Additive Manufacturing on Supply Chain, Reshoring, and Sustainability. *Clean. Logist. Supply Chain* **2023**, *7*, 100103. [CrossRef]
48. Kantaros, A.; Ganetsos, T.; Petrescu, F.I.T.; Ungureanu, L.M.; Munteanu, I.S. Post-Production Finishing Processes Utilized in 3D Printing Technologies. *Processes* **2024**, *12*, 595. [CrossRef]
49. Ge, J.; Pillay, S.; Ning, H. Post-Process Treatments for Additive-Manufactured Metallic Structures: A Comprehensive Review. *J. Mater. Eng. Perform.* **2023**, *32*, 7073–7122. [CrossRef]
50. Jin, L.; Zhai, X.; Wang, K.; Zhang, K.; Wu, D.; Nazir, A.; Jiang, J.; Liao, W.-H. Big Data, Machine Learning, and Digital Twin Assisted Additive Manufacturing: A Review. *Mater. Des.* **2024**, *244*, 113086. [CrossRef]
51. Peng, S.; Li, T.; Wang, X.; Dong, M.; Liu, Z.; Shi, J.; Zhang, H. Toward a Sustainable Impeller Production: Environmental Impact Comparison of Different Impeller Manufacturing Methods. *J. Ind. Ecol.* **2017**, *21*, S216–S229. [CrossRef]
52. Andrearczyk, A.; Bagiński, P.; Klonowicz, P. Numerical and Experimental Investigations of a Turbocharger with a Compressor Wheel Made of Additively Manufactured Plastic. *Int. J. Mech. Sci.* **2020**, *178*, 105613. [CrossRef]
53. Parize, H.; Tardelli, J.D.C.; Bohner, L.; Sesma, N.; Muglia, V.A.; Dos Reis, A.C. Digital versus Conventional Workflow for the Fabrication of Physical Casts for Fixed Prosthodontics: A Systematic Review of Accuracy. *J. Prosthet. Dent.* **2022**, *128*, 25–32. [CrossRef]
54. Hernández, F.; Fragoso, A. Fabrication of a Stainless-Steel Pump Impeller by Integrated 3D Sand Printing and Casting: Mechanical Characterization and Performance Study in a Chemical Plant. *Appl. Sci.* **2022**, *12*, 3539. [CrossRef]
55. Yang, Z.; Zhu, L.; Ning, J.; Wang, S.; Xue, P.; Xu, P.; Dun, Y.; Xin, B.; Zhang, G. Revealing the Influence of Ultrasound/Heat Treatment on Microstructure Evolution and Tensile Failure Behavior in 3D-Printing of Inconel 718. *J. Mater. Process. Technol.* **2022**, *305*, 117574. [CrossRef]
56. Popa, I.-F.; Dobromirescu, C.; Vintila, I.S.; Tinca, I.; Mihai, D.; Canache, A.M.; Crunteanu, D.E. Hydraulic Performance Comparison of Centrifugal Closed Impellers Fabricated by Means of Additive Manufacturing and Classical Machining for Space Active Thermal Control Systems of Satellites. *Applied Sciences* **2024**, *14*, 9448. [CrossRef]
57. Makivskyi, O.S.; Kondus, V.Y.; Pitel, J.; Sotnyk, M.I.; Andrusiak, V.O.; Polkovnychenko, V.V.; Mushtai, M.V. The Influence of the Design Features of the Submersible Pump Rotor on the Vibration Reliability. *J. Eng. Sci.* **2024**, *11*, D1–D9. [CrossRef]
58. Cooper, C.; Booth, A.; Britten, N.; Garside, R. A Comparison of Results of Empirical Studies of Supplementary Search Techniques and Recommendations in Review Methodology Handbooks: A Methodological Review. *Syst. Rev.* **2017**, *6*, 1–16. [CrossRef] [PubMed]
59. Aguinis, H.; Ramani, R.S.; Alabduljader, N. Best-Practice Recommendations for Producers, Evaluators, and Users of Methodological Literature Reviews. *Organ. Res. Methods* **2023**, *26*, 46–76. [CrossRef]
60. Alexander, P.A. Methodological Guidance Paper: The Art and Science of Quality Systematic Reviews. *Rev. Educ. Res.* **2020**, *90*, 6–23. [CrossRef]

61. Scopus. Scopus—Document Search. Available online: https://www.scopus.com/standard/marketing.uri (accessed on 27 June 2024).
62. WoS. *Web of Science. WoS.*; Clarivate: London, UK, 2020.
63. VOSviewer. VOSviewer—Visualizing Scientific Landscapes. Available online: https://www.vosviewer.com/ (accessed on 27 June 2024).
64. Jiménez, M.; Romero, L.; Domínguez, I.A.; Espinosa, M.d.M.; Domínguez, M. Additive Manufacturing Technologies: An Overview about 3D Printing Methods and Future Prospects. *Complexity* **2019**, *2019*, 9656938. [CrossRef]
65. Systèmes, D. Introduction to 3D Printing–Additive Processes. *Dassault Syst.* **2018**. [CrossRef]
66. Adiaconitei, A.; Vintila, I.S.; Mihalache, R.; Paraschiv, A.; Frigioescu, T.; Vladut, M.; Pambaguian, L. A Study on Using the Additive Manufacturing Process for the Development of a Closed Pump Impeller for Mechanically Pumped Fluid Loop Systems. *Materials* **2021**, *14*, 967. [CrossRef]
67. Meli, E.; Rindi, A.; Ridolfi, A.; Furferi, R.; Buonamici, F.; Iurisci, G.; Corbò, S.; Cangioli, F. Design and Production of Innovative Turbomachinery Components via Topology Optimization and Additive Manufacturing. *Int. J. Rotating Mach.* **2019**, *2019*, 9546831. [CrossRef]
68. Allison, T.C.; Rimpel, A.M.; Moore, J.J.; Wilkes, J.C.; Pelton, R.; Wygant, K. Manufacturing and Testing Experience with Direct Metal Laser Sintering for Closed Centrifugal Compressor Impellers. In Proceedings of the 43rd Turbomachinery Symposium, Houston, TX, USA, 23–25 September 2014; Texas A&M University, Turbomachinery Laboratories: College Station, TX, USA, 2014.
69. Meli, E.; Furferi, R.; Rind, A.; Ridolfi, A.; Volpe, Y.; Buonamici, F. A General Framework for Designing 3D Impellers Using Topology Optimization and Additive Manufacturing. *IEEE Access* **2020**, *8*, 60259–60269. [CrossRef]
70. Lea, H.G.; Wooding, R.S.; Kuhr, S.; Rotella, J.; Córdova, J.L. Characterization of Properties of Laser Powder Bed Fusion Three-Dimensional-Printed Inconel 718 for Centrifugal Turbomachinery Applications. *J. Eng. Gas Turbine Power* **2023**, *145*, 061017. [CrossRef]
71. Jia, D.; Li, F.; Zhang, Y. 3D-Printing Process Design of Lattice Compressor Impeller Based on Residual Stress and Deformation. *Sci. Rep.* **2020**, *10*, 600. [CrossRef] [PubMed]
72. Zhang, Y.; Li, F.; Jia, D. Residual Stress and Deformation Analysis of Lattice Compressor Impeller Based on 3D Printing Simulation. *Mech. Adv. Mater. Struct.* **2022**, *29*, 717–731. [CrossRef]
73. Guo, J.; Wang, Y.; Wang, Y.; Peng, S.; Wang, F. Simulation Study on the Energy Utilization Efficiency of a Turbine Impeller Based on a Selective Laser Melting Process. *Appl. Sci.* **2023**, *13*, 10657. [CrossRef]
74. Singh, S.P.; Gupta, R.K.; Agarwal, A. Processing and Characterization of Al-Si-Mg Alloy Made through 3D Printing and Comparison with Equivalent Cast Alloy. *Mater. Today Proc.* **2022**, *67*, 422–430. [CrossRef]
75. Auyeskhan, U.; Lee, T.; Park, Y.; Kim, D.; Kim, N.; Kim, C.-S.; Kim, D.-H. Design Study for Performance Improvement of a Hybrid Pico Pelton Turbine and Its Additive Manufacturing Using a Laser Powder Bed Fusion Method. *Int. J. Interact. Des. Manuf. (IJIDeM)* **2024**, *18*, 107–117. [CrossRef]
76. Qu, A.; Li, F. Influence of 3D Printing on Compressor Impeller Fatigue Crack Propagation Life. *Int. J. Mech. Sci.* **2023**, *245*, 108107. [CrossRef]
77. Raghavan, S.; Dzugan, J.; Rzepa, S.; Podany, P.; Soh, N.; Hao, L.J.; Khan, N. Effect of Post-Treatment on Local Mechanical Properties of Additively Manufactured Impellers Made of Maraging Steel. *Rapid. Prototyp. J.* **2023**, *29*, 594–611. [CrossRef]
78. Ponticelli, G.S.; Tagliaferri, F.; Venettacci, S.; Horn, M.; Giannini, O.; Guarino, S. Re-Engineering of an Impeller for Submersible Electric Pump to Be Produced by Selective Laser Melting. *Appl. Sci.* **2021**, *11*, 7375. [CrossRef]
79. Huber, M.; Ess, J.; Hartmann, M.; Würms, A.; Rettberg, R.; Kränzler, T.; Löffel, K. Process Setup for Manufacturing of a Pump Impeller by Selective Laser Melting. In *Industrializing Additive Manufacturing, Proceedings of the Additive Manufacturing in Products and Applications-AMPA2017 1, Zurich, Switzerland, 13–15 September 2017*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 252–263.
80. Zhang, Y.; Li, F.; Jia, D. Lightweight Design and Static Analysis of Lattice Compressor Impeller. *Sci. Rep.* **2020**, *10*, 18394. [CrossRef]
81. Wu, S.-T.; Huang, P.-W.; Chang, T.-W.; Jiang, I.-H.; Tsai, M.-C. Application of Magnetic Metal 3-D Printing on the Integration of Axial-Flow Impeller Fan Motor Design. *IEEE Trans. Magn.* **2020**, *57*, 8201205. [CrossRef]
82. Bauer, D. Additive Manufacturing of Cryogenic Pump Impellers. In Proceedings of the Asia Turbomachinery & Pump Symposium, Lumpur, Malaysia, 23–26 May 2022; Turbomachinery Laboratory, Texas A&M Engineering Experiment Station: College Station, TX, USA, 2022.
83. Kim, E.-H.; Choi, H.-H.; Jung, Y.-G. Fabrication of a Ceramic Core for an Impeller Blade Using a 3D Printing Technique and Inorganic Binder. *J. Manuf. Process.* **2020**, *53*, 43–47. [CrossRef]
84. Chivel, Y.; Sudarev, A.; Konakov, V. Additive Manufacturing Technology of Ceramic Turbomachines. In Proceedings of the European Congress and Exhibition on Powder Metallurgy. European PM Conference Proceedings, Hamburg, Germany, 9–13 October 2016; The European Powder Metallurgy Association: Sandviken, Sweden, 2016; pp. 1–6.
85. Bin, L.I.; Huimin, L.; Yuhang, Z.; Yaxin, C.; Ming, Z.; Qinming, W.U.; Yong, Y. Research on Precision Casting Process and Performance of Impeller Based on SLS. *J. Xihua Univ. (Nat. Sci. Ed.)* **2023**, *42*, 71–77.
86. Špale, J.; Novotny, V.; Novotný, J. Experimental Development of Additively Manufactured Turboexpanders towards an Application in the ORC. In Proceedings of the Heat Powered Cycles Conference, Bilbao, Spain, 10–13 April 2022.
87. Wang, D.; Dong, A.; Zhu, G.; Shu, D.; Sun, J.; Li, F.; Sun, B. Rapid Casting of Complex Impeller Based on 3D Printing Wax Pattern and Simulation Optimization. *Int. J. Adv. Manuf. Technol.* **2019**, *100*, 2629–2635. [CrossRef]
88. Sudarev, A.; Konakov, V.; Chivel, Y. Selective Laser Sintering of Ceramic Turbomachine Components. *Procedia CIRP* **2018**, *74*, 264–267. [CrossRef]

89. Badum, L.; Prochaska, T.; Schwentenwein, M.; Cukurel, B. Ceramic and Metal Additive Manufacturing of Monolithic Rotors From SiAlON and Inconel and Comparison of Aerodynamic Performance for 300W Scale Microturbines. *J. Eng. Gas Turbine Power* **2024**, *146*, 021006. [CrossRef]
90. Stümpfl, D.; Ráž, K.; Streit, P.; Weiß, A.P. Additive manufacturing for fast prototyping of a velocity compounded radial re-entry turbine. In Proceedings of the 7th International Seminar on ORC Power System (ORC2023), Seville, Spain, 4–6 September 2023; pp. 13–22.
91. Liverani, A.; Caligiana, G.; Frizziero, L.; Francia, D.; Donnici, G.; Dhaimini, K. Design for Six Sigma (DFSS) for Additive Manufacturing Applied to an Innovative Multifunctional Fan. *Int. J. Interact. Des. Manuf. (IJIDeM)* **2019**, *13*, 309–330. [CrossRef]
92. Adach, M.; Sokołowski, P.; Piwowarczyk, T.; Nowak, K. Study on Geometry, Dimensional Accuracy and Structure of Parts Produced by Multi Jet Fusion. *Materials* **2021**, *14*, 4510. [CrossRef]
93. Tan, X.; Kok, Y.; Tor, S.B.; Chua, C.K. Application of Electron Beam Melting (EBM) in Additive Manufacturing of an Impeller. In Proceedings of the 1st International Conference on Progress in Additive Manufacturing (Pro-AM 2014), Singapore, 26–28 May 2014.
94. Klocke, F.; Klink, A.; Veselovac, D.; Aspinwall, D.K.; Soo, S.L.; Schmidt, M.; Schilp, J.; Levy, G.; Kruth, J.-P. Turbomachinery Component Manufacture by Application of Electrochemical, Electro-Physical and Photonic Processes. *CIRP Ann.* **2014**, *63*, 703–726. [CrossRef]
95. Mandil, G.; Le, V.T.; Paris, H.; Suard, M. Building New Entities from Existing Titanium Part by Electron Beam Melting: Microstructures and Mechanical Properties. *Int. J. Adv. Manuf. Technol.* **2016**, *85*, 1835–1846. [CrossRef]
96. Wang, P.; Nai, M.L.S.; Lu, S.; Bai, J.; Zhang, B.; Wei, J. Study of Direct Fabrication of a Ti-6Al-4V Impeller on a Wrought Ti-6Al-4V Plate by Electron Beam Melting. *Jom* **2017**, *69*, 2738–2744. [CrossRef]
97. Kahhal, P.; Jo, Y.-K.; Park, S.-H. Recent Progress in Remanufacturing Technologies Using Metal Additive Manufacturing Processes and Surface Treatment. *Int. J. Precis. Eng. Manuf. Green Technol.* **2024**, *11*, 625–658. [CrossRef]
98. Michaud, M.; Milan, P.J.; Vo, H.D. Low-Cost Rotating Experimentation in Compressor Aerodynamics Using Rapid Prototyping. *Int. J. Rotating Mach.* **2016**, *2016*, 8518904. [CrossRef]
99. Derrick, S.; Rauen, J.; Rodriguez, J.; Aller, B. The Dual Impeller Drive System (DIDS). In Proceedings of the ASEE North Central Sectional Conference, Pittsburgh, PA, USA, 27 March 2010; Marshall University: Pittsburgh, PA, USA, 2010; pp. 4C1–4C8.
100. Geiselhart, M. *Design for Manufacturing and Characterization of Small-Scale Turbomachinery Impellers*; Technical University of Denmark: Kongens Lyngby, Denmark, 2021.
101. Leicht, B.T.; Bohan, B.T.; Schauer, F.; Kemnitz, R.; Rueschhoff, L.M.; Lam, B.; Kemp, J.W.; Costakis, W. Manufacturing a Ceramic Turbine Rotor for a Compact Jet Engine. *J. Turbomach.* **2023**, *145*, 081009. [CrossRef]
102. Zhao, J.; Chu, W.; Song, T.; Bi, L.; Liu, J.; Han, Z.; Wang, Y.; Zhou, Q.; Li, L. Digital Light Processing of High-Strength Si3N4 Ceramics: Role of Particle Grading on Slurries Curing and Mechanical Properties. *Ceram Int.* **2024**, *50*, 22722–22732. [CrossRef]
103. Ivanovich, S.M.; Dmitrievich, K.A.; Aleksandrovna, K.I.; Konstantinovich, S.F. Study of Impeller Design Parameters Effect on the Axial Thrust of a Centrifugal Electric Pump Assembly. *Sib. Aerosp. Mag.* **2020**, *21*, 389–399.
104. Zhu, X.; Tong, X.; Wang, F. Rapid Investment Casting Technology of Closed Impeller Based on Digital Light Processing (DLP) 3D Printing. *Spec. Cast. Nonferrous Alloys* **2021**, *41*, 1370–1374.
105. González Barrio, H. Metholology for Hybrid Manufacturing of Turbomachinery Integral Rotary Components in Thermoresistant Super Alloys. Ph.D. Thesis, Universidad del País Vasco-Euskal Herriko Unibertsitatea, Leioa, Spain, 2019.
106. Soo, A.; Ali, S.M.; Shon, H.K. 3D Printing for Membrane Desalination: Challenges and Future Prospects. *Desalination* **2021**, *520*, 115366. [CrossRef]
107. Li, C.; Wu, B.; Zhang, Z.; Zhang, Y. A Novel Process Planning Method of 3+ 2-Axis Additive Manufacturing for Aero-Engine Blade Based on Machine Learning. *J. Intell. Manuf.* **2023**, *34*, 2027–2042. [CrossRef]
108. Pfeil, A.; Siegfarth, M.; Pusch, T.P.; Barbé, L.; Geiskopf, F.; Renaud, P. Design and Experimental Characterization of Hydraulically Actuated Revolute Joint Based on Multimaterial Additive Manufacturing. *J. Mech. Des.* **2022**, *144*, 055001. [CrossRef]
109. Jiang, C.; Fleck, B.A.; Lipsett, M.G. Rapid Wear Modelling in a Slurry Pump Using Soft 3D Impeller Material. *Energies* **2020**, *13*, 3264. [CrossRef]
110. Daabo, A.M.; Hassan, A.A.; Bashir, M.A.; Hamza, H.; Salim, S.; Koprulu, A.; Badawy, T.; Mahmoud, S.; Al-Dadah, R. Experimental Study and 3D Optimization of Small-Scale Solar-Powered Radial Turbine Using 3D Printing Technology. *Machines* **2023**, *11*, 817. [CrossRef]
111. Nishida, M.; Negishi, T.; Sakota, D.; Kosaka, R.; Maruyama, O.; Hyakutake, T.; Kuwana, K.; Yamane, T. Properties of a Monopivot Centrifugal Blood Pump Manufactured by 3D Printing. *J. Artif. Organs* **2016**, *19*, 322–329. [CrossRef] [PubMed]
112. Udroiu, R.; Nedelcu, A.; Deaky, B. Rapid Manufacturing by Polyjet Technology of Customized Turbines for Renewable Energy Generation. *Environ. Eng. Manag. J.* **2011**, *10*, 1387–1394. [CrossRef]
113. Aruna Prabha, K.; Sai Rohit, P.; Nitturi, S.C.; Nithin, B. Manufacturing of 3 D Shrouded Impeller of a Centrifugal Compressor on 3D-Printing Machine Using FDM Technology. In Proceedings of the Materials Science and Engineering Conference Series, Bapatla, Andhra, 7–8 May 2021; Volume 1012, p. 012039.
114. Tamburrino, F.; Barone, S.; Paoli, A.; Razionale, A.V. Post-Processing Treatments to Enhance Additively Manufactured Polymeric Parts: A Review. *Virtual Phys. Prototyp.* **2021**, *16*, 221–254. [CrossRef]

115. Micha Premkumar, T.; Pushpak, V.; Vamsi Krishna, K.; Govardhan Reddy, D.; Sudheer Kumar, N.; Hariram, V.; Seralathan, S.; Nakandhrakumar, R.S. Design and Fusion Deposit Modelling of Radial Flow Centrifugal Pump. *Mater. Today Proc.* **2020**, *33*, 3497–3503. [CrossRef]
116. Choe, C.-M.; Yang, W.-C.; Kim, U.-H.; Ri, B.-G.; Om, M.-S. Manufacture of Centrifugal Compressor Impeller Using FDM and Investment Casting. *Int. J. Adv. Manuf. Technol.* **2022**, *118*, 173–181. [CrossRef]
117. Sedykh, L.V.; Borisov, P.V.; Pashkov, A.N.; Gorbatyuk, N.V.; Surkova, R.Y.; Mamatkulov, Z.K. Development of Flotation Machine Impeller on the Basis of Additive Technologies. *Steel Transl.* **2021**, *51*, 308–313. [CrossRef]
118. Jabłońska, M.; Jurczak, W.; Ozimina, D.; Adamiak, M. Increasing the Operational Reliability of a Ship by Using a Composite Impeller in the Event of Hydrophore Pump Failure. *Eksploat. I Niezawodn.* **2023**, *25*. [CrossRef]
119. Daniyan, I.A.; Muvunzi, R.; Fameso, F.; Mpofu, K.; Ale, F. Computer Aided Modelling and Investigation of the Performance of a Pump Impeller Produced Using Fused Deposition Modelling. In Proceedings of the 2023 14th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT), Cape Town, South Africa, 26–28 May 2023; pp. 244–249.
120. Sitte, D.; Sutanto, H. Performance Analysis of Hydraulic Machines Using Impellers Made from Conventional Steel and 3D Printing Co-Polymer. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Sanya, China, 12–14 November 2021; IOP Publishing: Bristol, UK, 2021; Volume 1115, p. 012049.
121. Polák, M. Behaviour of 3D Printed Impellers in Performance Tests of Hydrodynamic Pump. In Proceedings of the 7th International Conference on Trends in Agricultural Engineering, Prague, Czech Republic, 17–20 September 2019; pp. 17–20.
122. Do, T.; Bauder, T.J.; Suen, H.; Rego, K.; Yeom, J.; Kwon, P. Additively Manufactured Full-Density Stainless Steel 316L with Binder Jet Printing. In Proceedings of the International Manufacturing Science and Engineering Conference, College Station, TX, USA, 18–22 June 2018; American Society of Mechanical Engineers: New York, NY, USA, 2018; Volume 51357, p. V001T01A017.
123. Jayawardane, H.; Davies, I.J.; Gamage, J.R.; John, M.; Biswas, W.K. Investigating the 'Techno-Eco-Efficiency'Performance of Pump Impellers: Metal 3D Printing vs. CNC Machining. *Int. J. Adv. Manuf. Technol.* **2022**, *121*, 6811–6836. [CrossRef]
124. Sinha, A.; Swain, B.; Behera, A.; Mallick, P.; Samal, S.K.; Vishwanatha, H.M.; Behera, A. A Review on the Processing of Aero-Turbine Blade Using 3D Print Techniques. *J. Manuf. Mater. Process.* **2022**, *6*, 16. [CrossRef]
125. Pakle, S.; Jiang, K. Design of a High-Performance Centrifugal Compressor with New Surge Margin Improvement Technique for High Speed Turbomachinery. *Propuls. Power Res.* **2018**, *7*, 19–29. [CrossRef]
126. Zinchenko, A.; Baiul, K.; Krot, P.; Khudyakov, A.; Vashchenko, S.; Banasiewicz, A.; Wróblewski, A. Materials Selection and Design Options Analysis for a Centrifugal Fan Impeller in a Horizontal Conveyor Dryer. *Materials* **2021**, *14*, 6696. [CrossRef]
127. Sun, X.; Yan, Y.; Zhang, L.; Ma, G.; Liu, Y.; Yu, Y.; An, Q.; Tao, S. Direct 3D Printing of Reactive Agitating Impellers for the Convenient Treatment of Various Pollutants in Water. *Adv. Mater. Interfaces* **2018**, *5*, 1701626. [CrossRef]
128. Mansour, G.; Papageorgiou, V.; Tzetzis, D. Carbon Fiber Polymer Reinforced 3D Printed Composites for Centrifugal Pump Impeller Manufacturing. *Technologies* **2024**, *12*, 48. [CrossRef]
129. Jurković, K.; Schauperl, Z.; Šolić, S.; Bauer, B. Numerical Simulation of Sand Casting of Stainless Steel Pump Impeller. *Metals* **2024**, *14*, 435. [CrossRef]
130. Kennedy, F.E.; Ye, Y.; Baker, I.; White, R.R.; Barry, R.L.; Tang, A.Y.; Song, M. Development of a New Cryogenic Tribotester and Its Application to the Study of Cryogenic Wear of AISI 316 Stainless Steel. *Wear* **2022**, *496–497*, 204309. [CrossRef]
131. De Bartolomeis, A.; Newman, S.T.; Biermann, D.; Shokrani, A. State-of-the-Art Cooling and Lubrication for Machining Inconel 718. *J. Manuf. Sci. Eng.* **2021**, *143*, 050801. [CrossRef]
132. Raddatz, M.; Holländer, D.; Gampe, U. Innovative Material Testing Based on Small-Scale Specimens and Application for Turbomachinery Components. In *Turbo Expo: Power for Land, Sea, and Air*; American Society of Mechanical Engineers: New York, NY, USA, 2017; Volume 50923, p. V07AT31A004.
133. Córdova, J.L. Additive Manufacturing of Centrifugal Impellers for Solid Oxide Fuel Cell Anode Offgas Recycle Blowers. In *Turbo Expo: Power for Land, Sea, and Air*; American Society of Mechanical Engineers: New York, NY, USA, 2022; Volume 86052, p. V007T17A027.
134. Pegues, J.W.; Shao, S.; Shamsaei, N.; Sanaei, N.; Fatemi, A.; Warner, D.H.; Li, P.; Phan, N. Fatigue of Additive Manufactured Ti-6Al-4V, Part I: The Effects of Powder Feedstock, Manufacturing, and Post-Process Conditions on the Resulting Microstructure and Defects. *Int. J. Fatigue* **2020**, *132*, 105358. [CrossRef]
135. Wang, J.; Sama, S.R.; Lynch, P.C.; Manogharan, G. Design and Topology Optimization of 3D-Printed Wax Patterns for Rapid Investment Casting. *Procedia Manuf.* **2019**, *34*, 683–694. [CrossRef]
136. Rettberg, R.; Kraenzler, T. Hybrid Manufacturing: A New Additive Manufacturing Approach for Closed Pump Impellers. In *Industrializing Additive Manufacturing, Proceedings of the AMPA2020, Zurich, Switzerland, 1–3 September 2020*; Springer: Cham, Switzerland, 2021; pp. 146–159.
137. Li, H.; Zhang, Y. Lightweight Design of the Transonic Centrifugal Impeller Based on Fluid–Structure Coupling. *Phys. Fluids* **2022**, *34*, 107109. [CrossRef]
138. Kanesund, J.; Brodin, H.; Johansson, S. High Temperature Corrosion Influence on Deformation and Damage Mechanisms in Turbine Blades Made of IN-792 during Service. *Eng. Fail. Anal.* **2020**, *110*, 104388. [CrossRef]
139. Zhuk, Y. Nanostructured CVD W/WC Coating Protects Steam and Gas Turbine Blades Against Water Droplet Erosion. In *Turbo Expo: Power for Land, Sea, and Air*; American Society of Mechanical Engineers: New York, NY, USA, 2022; Volume 86052, p. V007T17A003.

140. Soffel, F.; Lin, Y.; Keller, D.; Egorov, S.; Wegener, K. Laser Remelting Process Simulation and Optimization for Additive Manufacturing of Nickel-Based Super Alloys. *Materials* **2021**, *15*, 177. [CrossRef] [PubMed]
141. Menon, N.; Mahdi, T.H.; Basak, A. Microstructure of IN738LC Fabricated Using Laser Powder Bed Fusion Additive Manufacturing. *J. Turbomach.* **2022**, *144*, 031011. [CrossRef]
142. Stella, P.; Ceccanti, F.; Cappuccini, F.; Bellacci, M.; Kemble, S.; Biccari, D.V.; Masi, G. Powder Metallurgy and Additive Manufacturing for Compressors and Pumps: A New Manufacturing Paradigm for Corrosion and Heat Resistant Alloys. In Proceedings of the Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, United Arab Emirates, 31 October–3 November 2022; SPE: Kuala Lumpur, Malaysia, 2022; p. D031S082R001.
143. Andrearczyk, A.; Konieczny, B.; Sokołowski, J. Additively Manufactured Parts Made of a Polymer Material Used for the Experimental Verification of a Component of a High-Speed Machine with an Optimised Geometry—Preliminary Research. *Polymers* **2020**, *13*, 137. [CrossRef]
144. Katiyar, P.C.; Singh, B.P.; Chhabra, M.; Kumar, N.; Parle, D. Analysis of Tensile Strength of Thin ABS Specimens 3-D Printed in Various Build Orientations for Turbomachinery Applications. *Int. J. Interact. Des. Manuf. (IJIDeM)* **2024**, 1–13. [CrossRef]
145. Vyacheslav, S.; Iurii, M.; Ilya, K. Prototyping Centrifugal Microcompressors Using Additive Technology. In *AIP Conference Proceedings*; AIP Publishing: Melville, NY, USA, 2023; Volume 2833.
146. Warner, J.; Celli, D.; Scott-Emuakpor, O.; George, T.; Tomlin, T. Fused Deposition Modeling Fabrication Evaluation of a TI-6AL-4V Centrifugal Compressor. *J. Eng. Gas Turbine Power* **2023**, *145*, 031008. [CrossRef]
147. Iyankumar, R.; Mohanavel, V.; Vinoth, N.; Vinoth, T. Modeling and Assessment of Pump Impeller. *Mater. Today Proc.* **2020**, *33*, 3226–3233. [CrossRef]
148. Jiang, C. Investigating Impeller Wear and Its Effect on Pump Performance Using Soft Materials. Master's Thesis, University of Alberta, Edmonton, AB, Canada, 2019.
149. Akdemir, B.; Kayisoglu, B.; Kocoglu, S. Effect of Impeller Materials on Centrifugal Pump Characteristics. *Agric. Mech. Asia Afr. Lat. Am.* **2006**, *37*, 62.
150. Fernández, S.; Jiménez, M.; Porras, J.; Romero, L.; Espinosa, M.M.; Domínguez, M. Additive Manufacturing and Performance of Functional Hydraulic Pump Impellers in Fused Deposition Modeling Technology. *J. Mech. Des.* **2016**, *138*, 024501. [CrossRef]
151. Bauer, A.P. Design, Development, and Testing of a Low Cost, Additively-Manufactured, Centrifugal Compressor, Air Force Institute of Technology. 2020. Available online: https://scholar.afit.edu/etd/3208 (accessed on 21 November 2024).
152. Boccini, E.; Furferi, R.; Governi, L.; Meli, E.; Ridolfi, A.; Rindi, A.; Volpe, Y. Toward the Integration of Lattice Structure-Based Topology Optimization and Additive Manufacturing for the Design of Turbomachinery Components. *Adv. Mech. Eng.* **2019**, *11*, 1687814019859789. [CrossRef]
153. Castro, M.T.; Ocon, J.D. Novel Designs of Blade Mixer Impellers from the Discrete Element Method and Topology Optimization. *Chem. Eng. J.* **2024**, *490*, 151863. [CrossRef]
154. Sword, J.I.; Galloway, A.; Toumpis, A. Analysis of Environmental Impact and Mechanical Properties of Inconel 625 Produced Using Wire Arc Additive Manufacturing. *Sustainability* **2024**, *16*, 4178. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.