3D-Printed Polymeric Spare Parts for Industrial Applications: A State-of-the-Art Review

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ABSTRACT

3D-Printed polymers are already being widely used in different disciplines. Producing component and spare parts proves to be one of its more critical functions. This paper discusses 3D-printed polymeric component and spare parts in various industries such as automotive, aerospace, maritime, medical, and manufacturing, as well as the challenges being faced in the adoption of the 3D printing technology in these industries. The common 3D printing technologies and materials used to produce spare parts are summarized and briefly discussed. Lastly, the opportunities, challenges, and future outlook of using 3D printing in the production of spare parts are presented.

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Email Address: jrcdizon@bpsu.edu.ph
Date received: September 04, 2022
Date revised: November 09, 2022
Date accepted: November 13, 2022

INTRODUCTION

Additive Manufacturing (AM), commonly referred to as 3D printing, is an innovative and revolutionary technology that plays a big role in the Industry 4.0. From design approaches to smart manufacturing techniques, it has profound implications on social (Ratto and Ree, 2012; Jiang et al., 2017), environmental (Tijing et al., 2021; OECD, 2017), demographic and geopolitical aspects (Campbell et al., 2012; Pierrakakis et al., 2015). It has the potential to transform present corporate strategies and policies of manufacturing businesses (Jiang et al., 2017), with a

KEYWORDS

3D Printing, Additive Manufacturing, Industrial Applications, Polymers, Spare Parts

great potential for environmental benefits by minimizing wastes (transport, materials and energy) in a production set-up (Lupton, 2017). Through its disruptive nature, it can solve demographic problems in supply chain and logistics, substantially reduce manufacturing lead times, introduce new complex designs, and meet complex customer demands that might possibly lead to altering global economic order in the coming years (Attaran, 2017; Garrett, 2014).

While 3D printing initially began with prototyping low volume production of customized parts (Ramya and Vanapalli, 2016), it led to a wide range of industry applications such as industrial automation (Savastano et al., 2016; Lim et al., 2016; Lecklider, 2016), in the aviation and aerospace sectors (Lim et al., 2016; Nickels, 2015; Joshi and Sheikh, 2015; Gasman, 2019), in the maritime sector (Kostidi and Nikitakos, 2017; Kostidi and Nikitakos, 2019; Strickland, 2016; Vujović et al., 2018; Taş and Şener, 2019), and medical industries (Muir and Haddud, 2018; Haleem and Javaid, 2020; Salmi et al., 2020; Advincula et al., 2020; Advincula et al., 2021). However, considerable advantages have yet to be demonstrated in these different industry sectors especially in high throughput manufacturing.

For instance, the automotive industry is known to develop new design trends quickly, which usually requires new tools (tool reshaping) to customize products (Sarvankar and Yewale, 2019). This has induced the automotive sector to progressively experiment with adopting additive manufacturing for rapid prototyping of spare parts (Eggenberger et al., 2018). Subsequently, it proved to be a solution that enables an adaptable production of customized spare parts without significantly affecting the cost and lead time (Sarvankar and Yewale, 2019).

The aviation and aerospace sectors are also reaping the benefits of 3D printing. Traditional manufacturing methods require a high level of supply chain management together with large machinery and workforce (Joshi and Sheikh, 2015). The aerospace sector requires more lightweight, more vital, and more durable components with zero-to-low material waste, which are the advantages offered by 3D printing (Kalender et al., 2019). Moreover, the complex geometry of engine parts and components is also the main factor driving the aerospace industry to further experiment with what additive manufacturing technology can uniquely offer.

The maritime industry, with characteristics similar to the aerospace and automotive sectors, also finds a way to adopt 3D-printed spare parts for shipbuilding, e.g., naval architectural and engineering design (Kostidi and Nikitakos, 2017). One study shows that a lightweight offshore vessel produced via 3D printing is lighter, cheaper, quick to create, and capable of optimizing a specific Eigen frequency, improving radar movement (Van der Zalm, 2017).

In the medical sector, 3D bioprinting is seen to have more significant potential in creating complex geometries and compound components of functional bioconstructs with widespread applications such as therapeutic investigation and organ transplantation (Mir and Nakamura, 2017). 3D printing also plays an important role in developing low-cost modern prosthetic device as an assistive technology for persons with disabilities (Diego et al., 2021). During the recent global COVID-19 pandemic that caused an unprecedented demand for medical supplies, this technology was able to address the shortage of medical devices, spare parts, and PPEs used for treatment and protection (Advincula et al., 2020).

The significant opportunities offered by additive manufacturing have led different industries to gradually adopt the concept of this disruptive technology. This review summarizes the production and application of 3D-printed spare parts in each industry to generate information that could lead to additional opportunities and answer some of the challenges faced in conventional manufacturing.

The 3D-printed spare parts available in the market and from scientific studies have been categorized and tabulated. A short discussion on the materials and technologies used for spare parts production is also presented. Meanwhile, the challenges and opportunities in each particular industry has been enumerated in this review to assess the feasibility of AM spare parts production. Finally, a discussion of future perspectives on the production and application of spare parts has also been included.

METHODOLOGY

In searching for related articles, journals, and data, a state-of-the-art review has been followed as a guide to conduct data gathering. A state-of-the-art review is a sub-type of a literature review that deals with current matters and/or recent challenges in a given area. This type of review offers new perspectives and identifies areas needing further research (Grant and Booth, 2009).

In this review, the current and relevant information related to 3D printing of spare parts have been gathered. A keyword search was used in various online sources, primarily scientific journal databases and credible websites. Some of the following keywords are: [[3D printing AND spare parts AND polymers]] or [[additive manufacturing AND spare parts AND polymers]] or [[3D printed spare parts AND components AND polymers]]. All the related articles gathered from the keyword search have been initially examined through abstract review, only relevant papers related to the 3D printing of spare parts were included. The selected papers were then analyzed and synthesized before concluding as final references. Moreover, citation snowballing or the search for additional related literature from the references of initially gathered articles was also performed. The detailed

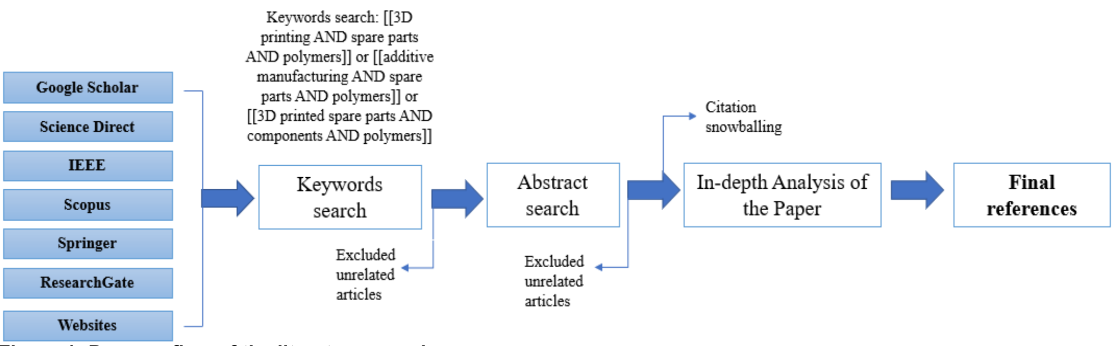

Figure 1: Process flow of the literature search

process flow chart of this state-of-the-art literature search is summarized in Fig. 1.

Overview of Additive Manufacturing

Additive Manufacturing or 3D printing has been defined as the successive addition of layers of material to create an object from a 3D design model (Valino et al., 2019). The process starts with preparing the desired 3D design model using 3D CAD software, which will export the model into a printable file such as .stl (Standard Tessellation Language) or .obj (Wavefront Object). Subsequently, the 3D model will be subjected to a slicing software to set the printing parameters, and to slice the model into multiple layers and convert the printable file into a type required by a particular printer (G-code). The printer will then fabricate the design one layer after another (Dizon et al., 2018). The printed object is often subjected to a post-processing method to improve its mechanical properties and aesthetic value (Dizon et al., 2021; Dizon et al., 2018).

AM technologies have continuously gained significant advances through various research conducted globally (Dizon et al., 2018). These studies include the type of materials used in printing, such as a review on utilizing high-performance polymer nanocomposites in different applications (de Leon et al., 2016), recent advancements in 3D printing biomaterials (Chia and Wu, 2015), combination of polyamide-12 and carbon black to enhance thermal and mechanical properties of 3D-printed objects (Espera et al., 2019), and the compatibility of cementitious material in 3D printing (Ma et al., 2018). As a result, advanced 3D printing technologies and materials are now introduced in various practical applications (Dizon et al., 2020). Multiple applications in different industries, including but not limited to medical, automation, aerospace, marine, and even 3D-printed electronics, are now being adopted (Espera et al., 2019).

Common 3D Printing Technologies Used for Spare Parts Production

Based on ASTM F2792, AM technologies are grouped into seven categories; namely, material extrusion, vat photopolymerization, powder bed fusion, material jetting, binder jetting, directed energy deposition, and sheet lamination (*Standard Terminology for Additive Manufacturing Technologies*, 2013; *3D Printing*, 2022).

Fused Filament Fabrication (FFF) also known as Fused Deposition Modelling (FDM), categorized under material extrusion, is the most widely used technology in different industries. This technology creates 3D-printed parts by extruding molten plastic filament layer by layer on a build platform. FDM is economical and can produce printed parts faster with a broader range of material selections than other AM technologies. Usually, desktop FDM 3D printers have a dimension of 200 x 200 x 200 mm, and dimensions larger than 1 m^3 for industrial FDM 3D printers (*3D Printing*, 2022; *Large Scale 3D Printing*, 2022).

The second most commonly-used technology is Stereolithography (SLA). Under Vat Photopolymerization technology (also known as resin 3D Printing), an SLA 3D printer uses an ultraviolet (UV) laser as light source to cure polymer resin selectively. Photosensitive thermoset polymers in liquid form are used in this type of 3D printer. When very high accuracy or a smooth surface finish is required in a 3D model, SLA remains the most cost-effective 3D printing technology (*3D Printing*, 2022).

Powder Bed Fusion (PBF) is also a commonly used AM technology. It uses thermal energy to "selectively" fuse areas in a powder bed. Multi Jet Fusion (MJF) uses powdered thermoplastics to create complex parts with high accuracy and fine details, making it one of the most chosen AM technology for industrial applications. On the other hand, Selective Laser Sintering (SLS) uses a thermoplastic polymer (in granular form) to selectively sinter. It can be a replacement for injection molding for small production runs. The heat source is the significant distinction between the two PBF technologies. MJF uses a fusing agent (ink) to absorb infrared light on the powder and then uses an infrared energy source to fuse the inked areas to the build platform, while SLS scans and sinters each cross-section using a laser (*3D Printing*, 2022).

Common 3D Printing Materials Used for Spare Parts Production

Polymers

The 3D printing materials used for making spare parts in industries including Automotive, Aerospace, Marine, Medical, and Manufacturing industries comes from a limited selection of plastics, composites, and metals. Most standard 3D-printed spare parts across several industries are made from thermoplastic and thermoset polymer materials since some materials are difficult to thermally control which is very important in 3D printing. The types of polymers that are at the forefront of spare parts production are the following: acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polyether ether ketone (PEEK), polyetherimide (PEI), polypropylene (PP), polycarbonate (PC), thermoplastic polyurethane (TPU) and polyamide (PA), and epoxy resin.

Acrylonitrile butadiene styrene (ABS) is an engineering thermoplastic polymer with a versatile property aside from being inexpensive, which is why it is advantageous to be used in a wide variety of industrial applications. It is valued for its high tensile strength and good resistance to impact and chemical degradation, allowing the ABS 3D-printed parts to withstand heavy applications and adverse environmental conditions. It also has excellent performance at high and low temperatures. ABS has a low melting point of around 200 ^{o}C, allowing it to be used easily in 3D printing processes (Peters, n.d.).

Polylactic acid (PLA) is a very versatile and inexpensive bioplastic just like ABS. However, PLA is less resistant to stress than ABS and less reliable for long-term wear and tear. But unlike ABS, PLA is less toxic and easier to print because of its lower melting temperature. PLA is the most popular 3D printing material because it can be 3D-printed by almost all FDM 3D printers. It is mainly used for prototyping and modeling or educational purposes (*What's the Difference Between PLA and ABS?*, 2022) and can also be used to make 3D-printed spare parts.

Polypropylene (PP) is a semi-rigid and lightweight material, which is considered for its elasticity, toughness, and resistance to fatigue failure. PP is also chemical resistant, making it a good option for making liquid containers. It has a relatively slippery surface making it suitable for low friction applications like gears (*Everything You Need to Know About Polypropylene (PP) Plastic*, 2016).

Polycarbonate (PC) is used extensively in FDM 3D printing due to its durability, high impact resistance, relatively lower weight, and high heat deflection property, making it suitable in high-temperature applications. In addition, it is commonly used in some applications where minimal flexibility is required. However, polycarbonate requires very high print temperatures. It is prone to warping during printing because of difficulties in adhesion on the build plate due to its high melting point and high susceptibility to absorbing moisture which can cause print defects (*Ultimate 3D Printing Materials Guide*, 2022). Despite these issues, 3D printing spare parts using polycarbonates is still possible.

Polyether ether ketone (PEEK) is a semi-crystalline thermoplastic known for its mechanical and thermomechanical properties. Its semi-crystalline structure keeps its mechanical characteristics even when subjected to higher temperatures. PEEK is heat and wear-resistant and can be used as a substitute for some metals due to its high weight-to-strength ratio, making its main application popular in the aerospace, medical, and automotive industries. PEEK is an established material used for the FDM 3D printing process. It has also become applicable for the SLS 3D printing process (Dizon et al., 2021).

Polyetherimide (PEI) is an amorphous engineering thermoplastic with characteristics similar to PEEK, such as high-temperature resistance, outstanding mechanical and electrical properties, and a high strength-to-weight ratio. PEI is a popular material for FDM 3D printers due to its good adhesive properties and chemical stability (Ma et al., 2018). In addition, PEI is a highly valued material in several industries like automotive, medical, and other industrial applications because it has high tensile strength, good flame resistance, and low smoke emission.

Thermoplastic polyurethane (TPU) is the most widely used type of thermoplastic elastomer (TPE) in 3D printing. TPU is highly flexible, but its degree of elasticity or rigidity depends on its chemical formulation. Moreover, TPU has excellent abrasion resistance, impact resistance, and chemical and thermal resistance properties. Also, this thermoplastic has excellent oil and grease resistance properties, which is suitable for producing hoses, gaskets, and seals. There are two main TPU material types: polyether polyurethane and polyester polyurethane. Both have different characteristics that are fit for specific applications (*TPU Material*, 2020). In recent years, the use of TPU by various industries such as automotive and aerospace industries have been increasing rapidly (Tuazon et al., 2022; Martinez et al., 2022).

Polyamide (PA) or commonly known as Nylon, is a synthetic thermoplastic that is an ideal choice for printing durable parts as it offers high tensile strength, high impact resistance, good abrasion resistance, and relatively high flexibility (Tuazon et al., 2022; Dizon et al., 2021). Moreover, polyamide is suitable for making functional prototypes with moving parts due to its low coefficient of friction. However, Nylon has a high melting point and is hygroscopic (i.e., quickly absorbs moisture), making it quite challenging to print. Nylon materials can be 3D-printed using material extrusion, multi-jet fusion, or powder bed fusion technology, depending on their form. PA 6, PA 11, and PA 12 are common types of Nylon. Among these types of Nylon, PA 6 is the most common and has excellent flexibility and resistance to impact and abrasion, while PA 11 has outstanding resistance to light, UV, and impact, and PA 12 has exceptional strength, stiffness, and thermal properties. The properties of Nylon in powdered form can be improved by combining it with other materials such as glass, carbon fiber particles, or aluminum to produce a reinforced PA powder with improved characteristics. Goodridge et al. reported that laser-sintered polyamides' elastic modulus and tensile strength are almost like that of injection molded parts (Goodridge et al., 2012). Generally, PA is valued in engineering and OEM fabrication due to its excellent mechanical properties and chemical stability. And due to its biocompatibility with human tissues, PA has become an increasingly valuable material used for medical applications (Dizon et al., 2021).

Photopolymer resins change their state and properties when exposed to UV light; that is why these materials are primarily used in Stereolithography (SLA) 3D printing and Material Jetting (MJ) technologies (Crivello and Reichmanis, 2014; Ngo et al., 2018). A photopolymer resin provides smooth and delicate finished parts with high resolution and good thermal stability due to its high crosslinking density. Photopolymer resin, particularly epoxy resin, has been valued for its application as matrix or base material for carbon fiber composites 3D printing material due to its high adhesive strength and good chemical and heat resistance (Jin et al., 2015).

Non-Polymer Materials

Aside from polymeric materials, composite and metal materials are also briefly discussed in this paper since both are now gaining considerable growth for spare parts use in across several industries.

Composite materials have gained interest and application in making 3D-printed spare parts due to their exceptional versatility and tailorable properties. Composite materials usually consist of two or more types, e.g., natural and high-performance synthetic fibers like carbon and glass. These fibers reinforce polymer materials (which serve as matrices) to produce a new material with enhanced properties. Both carbon fiber-reinforced polymer composites and glass fiber-reinforced polymer composites show great potential and are applicable for 3D printing (Tuazon et al., 2022). The composite structures of carbon fiber-reinforced polymers are used due to their durability, crash worthiness, toughness, and aesthetic beauty, as well as their high applicability for lightweight components that support heavy loads as they provide strength and rigidity similar to those made of 6061 Aluminum (Ahmad et al., 2020).

On the other hand, the glass fiber-reinforced polymer composites are cost-effective and provide excellent durability, strength, and resistance to impact. In addition, glass fiber-reinforced polymer composites are very suitable for 3D printing applications due to their exceptional thermal stability (Liu et al., 2015; Ahmad et al., 2020; Rajak et al., 2019). Applications of 3D-printed composite materials have been found in prototyping, tooling, and end-use part manufacturing.

Metal-based 3D printing is now becoming relevant in many manufacturing industries because it allows producing parts with almost similar strength to conventionally-produced metallic elements (*Can 3D Printing Use Metal?, 2022*), making it very useful in manufacturing customized and complicated spare parts. Metal 3D printing also offers a solution for the light weighting of parts used in various industries, including aerospace and automotive. Metal 3D printing is usually based on powder bed fusion technology using powder metal (*Metal 3D printing, 2022*). The following metals are in powder form: titanium alloys, stainless steel, aluminum, and aluminum alloys, copper, cobalt chrome, nickel-based alloys. Precious metals like gold, platinum, palladium, and silver are already being used for 3D printing (*Metal Powders for Additive Manufacturing*, 2022). Recently, a different metal 3D printing technology called wire arc additive manufacturing (WAAM) has been making significant progress. Unlike the previously mentioned technology that uses powdered metal, WAAM uses a metal material in wire form, which is melted by an electric arc, like welding, as it is being deposited layer-by-layer, creating 3D objects. The metal wires most widely used in WAAM are titanium alloys, maraging steel, martensitic stainless steel, duplex stainless steel, austenitic stainless steel, SAE 316L stainless steel, aluminum alloys, and nickel alloys (Schwaar, 2022). In this review, some examples of spare parts using non-polymeric materials have been included to serve as a guide for materials scientists in developing new polymer materials with properties approaching those of composites and some metals.

3D-Printed Spare Parts in Different Industries

3D Printing Applications in the Automotive Industry

3D printing applications in the automotive industry have considerably grown in recent years, wherein previously it was mainly used for rapid prototyping and tooling. It now has a massive potential in the automotive industry for its cost-effective technology in developing high-quality and bespoke components that were previously not possible using traditional methods. 3D printing is currently gaining a lot of interest from automakers because of its design freedom, material options, light weighting capabilities, and cleaner, safer, and shorter lead time production (Nichols, 2019). Ford Motors, Toyota, Kia, Volkswagen, Bugatti, Mercedes, Honda Motor Corporation, and many other automakers and suppliers use 3D printing for their product development. Ford Motor Co. used 3D printing to maximize the efficiency of its EcoBoost engine lineup; while Toyota Motor Corp. used 3D printing to showcase their concept for the FT-1 car and examine the quality and efficiency of the engine oils and the production of the interior cavity by creating a transparent version of the engines. Further research is being conducted to identify other opportunities that additive manufacturing can offer in the automotive sector (Tuazon et al., 2022). The automotive industry is gradually adopting 3D-printed parts to replace various components, such as spare parts which have been traditionally manufactured before, since thousands of uniquely designed parts and different fixtures, jigs, and tools are used in automotive manufacturing (Schmitt et al., 2020).

For instance, rail spare parts which include tram drivers' arm rests, tram vehicle exterior and a suspension bracket have already been 3D-printed using FFF and PBF technology. It has been created as a replacement for rail components that are several decades old and are often hard to purchase due to unavailability in the market. The 3D printing of spare parts is said to be cost and time-efficient and shows an increase in durability and flexibility of the part. For instance, it has been used to design an ergonomic arm rest (Davies, 2020). While custom locking wheel lug nuts used in cars were also 3D-printed by Ford Company; i.e., includes second-level security features which is personalized based on the owner's voice (*Ford Motor company*, 2022). Furthermore, an alternator bracket and a brake caliper has also been 3D-printed. (Sarvankar and Yewale, 2019). More examples of automotive 3D-printed spare parts produced, customized, or are commercially available are listed in Table 1.

3D Printing Applications in the Aviation and Aerospace Industry

The aerospace industry is one of the sectors that pioneered the adoption of 3D printing in the production of aircraft parts (Martinez et al., 2022). Unlike any other industry with spare parts production that is primarily volume driven, aircraft components have characteristics of low-average demand rates and uncertainty in demand predictions (Brown, 1956). AM production is also an excellent way to replace rarely available stock aircraft parts that are no longer in production (Lim et al., 2016a). Moreover, Airbus, an aerospace corporation, confirmed that additive manufacturing helps reduce the components' weight by up to 55 percent, which also leads to a reduction in raw materials costs by up to 90 percent. Note that weight reduction is a significant factor in the aerospace industry, which also means less energy consumption (*Airbus Gets on Board with 3D Printing*, 2021).

In space applications, 3D printing offers the opportunity for on-demand production of aerospace components, making it timely and cost-efficient. It also allows the production of spare parts with complex part geometry while considering the engine components' durability and lightweight characteristics (Kalender et al., 2019). For instance, (Schiller, 2015) 3D-printed a jet engine fuel nozzle and liquid oxygen flange. Some other 3D-printed aerospace components are listed in Table 2.

3D Printing Applications in the Maritime Industry

The advancement offered by 3D printing in the aviation and aerospace sectors also created an opportunity in different sectors, particularly in the marine industry, which has notable similarities in spare parts applications. Recently, the practical applications and advantages of 3D printing in shipbuilding have already been recognized, including the benefits of producing parts and prototype models of ships (*3D Printing: Rising to the Challenge in Ship Design, Verdict Media Limited*, 2015). Moreover, 3D printing technology has already been successfully used to make high load-bearing parts for maritime applications, such as propellers and crane hooks (Gardner, 2021). It was also reported that 3D printing technology would ensure the supply of spare parts in the maritime sector, thus, improving its services and cost-effectiveness. In early 2019, a Joint Industry Project (JIP) was launched. This program develops a concept for the future of the 3D-printed spare parts supply chain; it also includes a case study for establishing a local 3D printing facility that can provide a large amount of on-demand marine spare parts that are frequently purchased. And by 2020, 3D-printed parts have been commercially delivered (Kostidi and Nikitakos, 2018).

3D printing leads to better design, as it offers flexibility in complex geometry parts and introduces more lightweight marine spare parts. 3D printing helps sustainability in terms of reducing waste generation and power consumption as it prevents the use of excessive and unnecessary materials, which is the case in subtractive manufacturing. It also plays a role in the supply chain, eliminating the need for additional transportation and warehousing (Bergsma et al., 2016). For instance, the first approved 3D-printed ship propeller with a diameter of 1.3 m and weight of approximately 180 kg has brought important developments in marine 3D-printed spare parts (Bayramoğlu et al., 2019). Other maritime applications are listed in Table 3.

3D Printing Applications in the Medical Industry

Several applications have been explored in different areas in the medical industry, such as implants, anatomical models, tissue engineering and regenerative medicines, customized prosthetics, tissue and organ fabrication, pharmaceutical research on drug formulation, and many more recent discoveries (Ventola, 2014). These applications have been possible due to the various benefits offered by 3D printing, including productivity enhancement, customization within medical products, drugs, or equipment, design and manufacturing processes, opportunities for collaborative efforts, and potential cost-effectiveness (Choonara et al., 2016).

In addition to the abovementioned benefits, the medical and healthcare industry also look forward to the following promising opportunities that can be offered by this transformative technology; (1) 3D printing can copy the natural structure of human skin at a much lower cost than the traditional process which in turn can help the cosmetics, cosmeceutical products and pharmaceutical products industries in various aspects (Shahrubudin et al., 2019), (2) it can also offer a wide range of applications in drug formulation including personalized drug dosing, novel dosage forms, 3D-printed polypills, personalized topical treatment devices, and complex drug release profiles (Kotta et al., 2018), (3) the possibility of using 3D printers has been explored in the fabrication of scaffolds with complex, customized geometries depending on the process of imaging techniques performed on patients which means it can achieve precise control on the patient's requirement (de Mori et al., 2018), (4) in tissue engineering, 3D printing technology can be

Table 1: 3D-Printed Spare Parts for the Automotive Industry

Automotive Spare Parts	Materials Used	Printers and 3D Printing Technology Used	Applications	Advantages and Disadvantages
Car parts/ components (mirrors, dashboards, bumpers, mechanical parts such as brackets, light brackets, and interior features) (Peels, 2017)	ABS, PEI, and PEEK	*Printing Technologies* • Fused Deposition Modelling (FDM) • Photopolymerization, Selective laser sintering (SLA) *Printers* • Ultimaker 2, Formlabs, • Raise3D printer, • Customized SLA machine, Modified Ultimaker printer	3d printing classic car components whose parts are already unavailable and some customizable features of relatively recent cars	*Advantages* • All parts are modified depending on the customers' interests. • A firmware for custom units and for optimizing high-temperature materials. *Disadvantages* • Finishing and sanding areas are time-consuming and not cost-effective.
Aerodynamic car parts (*3D Printed Car Replacement Parts Are Fueling the Automotive Revolution*, 2020)	ABS and PLA	*Printing Technologies* • Fused Deposition Modelling (FDM), • Selective Laser Sintering (SLS) • Stereolithography (SLA), • Polyjet	Excellent prototyping and manufacturing of aerodynamic replacement parts considering customer personalization in the sports vehicle industry.	*Advantages* • The automotive industry can print and test a range of aerodynamic parts that can help achieve optimum performance while being more efficient than the traditional process.
Train interior carriage parts (armrests and grab handles) (Davies, 2019)	Not Specified	Not Specified	3d printing train components are unavailable in the market due to minimum demands or inaccessible suppliers	*Advantages* • The armrests were produced within a week; a 94% lead time reduction. • The supply chain is faster, cheaper, and responsive to operators' needs.
Wheelset bearing cover for a Class 294 locomotive (*How 3D Printing Is Transforming the Spare Parts Industry [2021 Update]*, 2021)	Metal Wire	*Printing Technologies* • Wire Arc Additive Manufacturing (WAAM) technology	3d printing a missing old model spare part is hard to procure, causing more extended vehicle downtime.	*Advantages* • Increased part availability • lower manufacturing costs • time-efficient

Automotive Spare Parts	Materials Used	Printers and 3D Printing Technology Used	Applications	Advantages and Disadvantages
Porsche Classic supplies parts for vintage and out-of-production models (*How 3D Printing Is Transforming the Spare Parts Industry [2021 Update]*, 2021)	Metal, Polymer	Not Specified	Porsche: 3D printing spare parts for classic cars	*Advantages* • Cost-effective • Increased operational efficiency • Optimized inventory
Porsche's racing-style bucket seat for various 911 and 718 models (Vijayenthiran, 2022; Mullen 2021)	Polyurethane-based materials	Not Specified	Porsche wants to expand seat customization beyond firmness and color by personalizing the seat to the customer's specific body contour.	• *Advantages* • 8% lighter than a conventionally produced bucket seat. • 3D printing allows customization of car seats for individual customers.
2020 Shelby GT500 two structural brake components (Boissonneault, 2019; *Ford Motor company, 2022*)	EPX (epoxy) 82 material	*Printing Technologies* • Carbon's Digital Light Synthesis (DLS) 3D printing	Ford has made steps to integrate 3D printing into its product development cycle and manufacturing applications.	*Advantages* • The 3D-printed parts have passed all Ford's performance standards and requirements.
Volkswagen Autoeuropa: 3D-printed manufacturing tools (Jigs, Fixtures, etc.) (*10 Exciting Examples of 3D Printing in the Automotive Industry in 2021*, 2021)	Not Specified	*Printers* • Ultimaker's desktop 3D printers	When it comes to manufacturing aids, 3D printing is rapidly growing as an alternative to more established ways of manufacturing tools.	*Advantages* • Producing its tooling internally reduces tool production costs for the car manufacturer by 90% — and cuts lead times from weeks to a few days. • Using 3D printing for tooling has saved Volkswagen nearly €325,000 in 2017 while improving ergonomics, productivity, and operator satisfaction.

Table 2: 3D-Printed Spare Parts in the Aviation and Aerospace Industry

Aviation and Aerospace Spare Parts	Materials Used	Printer and 3D Printing Technologies Used	Applications	Advantages and Disadvantages
NASA Multipurpose Precision Maintenance Tool (Including different sized wrenches, drives to attach sockets, a precision measuring tool for wire gauges, and a single-edged wire stripper) (Rainey, 2017)	Not Specified	Not Specified	A device was created to be available for astronauts in space.	*Advantages* • The feasibility of building currently required spare parts in space • Cost-effective and time efficient
NASA rocket engine injector (Newswire, 2013)	Fine metallic powders	*Printing technologies* • Powder Bed Fusion (PBF) • Selective Laser Melting (SLM)	An innovating, expanding, advaa 1nced, flying hardware for use in NASA's future missions.	*Advantages* • Cast-effective and time efficient
Business Premier bumper part (*How 3D Printing Is Transforming the Spare Parts Industry [2021 Update]*, 2021)	Not Specified	*Printing technologies* • Fused Deposition Modelling (FDM)	Localized and on-demand 3D printing of aircraft spare parts	*Advantages* • Cost-effective and time efficient
Parts of Jet Engines (fuel injecting nozzle, sensors, blade, heat exchangers, etc.) (M. Rokonuzzaman, 2020)	Not Specified	Not Specified	Mass-production of Jet engine parts via General Electric company	Advantages • The fuel injecting nozzle has been printed in a single piece instead of 20 welded separate parts, resulting in a reduced weight up to 25% • Increased durability • 30% cost-efficient

Table 3: 3D-Printed Spare Parts for the Maritime Industry

Maritime Industry Spare Parts	Materials Used	Printer and 3D Printing Technologies Used	Applications	Advantages and Disadvantages
Propellers for high-drag AUV (D'Epagnier et al., 2007)	ABS/polycarbonate blend	*Printing technologies* Fused Deposition Modelling (FDM)	A code has been developed for different applications of propeller designs, including AUV and ROV thrusters and conventional propellers.	*Advantages* • It is designed as a parametric design tool that engineers may use in designing and making a propeller. • All propeller designs have been constructed and subjected to a performance tester.
Wings and tail for low-drag AUV (Barngrover et al., 2011)	Plastic coated with epoxy	Not Specified	The Stingray Autonomous Underwater Vehicle (AUV) was designed as a cost-effective solution for Ecological Monitoring	*Advantages* • The AUV design is compact and lightweight, with a unique design implementation. • It is easy to drag along the water and allows the vehicle to glide.
Propellers and motor transmission parts for AUV (Ridol et al., 2012)	Plastic	Not Specified	New motor transmission and propeller designs have been introduced and built in the MDM Lab (Italy) using a 3D printer.	*Advantages* • A water-tight characteristic has been obtained from the new design. A tendon-driven hand designed for underwater manipulation controlled by mobile gestures. • The magnetic coupling has limited the maximum transmissible torque of the motor transmission. *Disadvantages* • The new design is quite heavy than the usual • It omits magnetic noise caused by vehicle instrumentation • There is a short torque transmission delay recorded between the motor and propeller.
Robotic hand for underwater manipulation (Stuart et al., 2014)	Visijet Crystal	*Printers* MultiJet (Projet 3500)	A tendon-driven hand designed for underwater manipulation controlled by a mobile gesture	*Advantages* • It allows the fingers to grasp small, slippery objects underwater and secure large objects with full arm strength.

utilized to restore, improve, replace and maintain the different tissue functions taking into consideration the interconnected pore network, appropriate surface chemistry, biocompatibility and good mechanical properties (Shahrubudin et al., 2019), (5) in the problem of organ failure which is a critical medical condition that currently relies primarily on organ transplantation, 3D printing can be used to form a replacement organ based on the cells taken from the patient, eliminating the risk of chronic shortage of human organs for transplant and provides an opportunity for overcoming cost and time challenges (Ventola, 2014), (6) 3D printing can also promote more reliable and accurate data to help accelerate cancer research (Shahrubudin et al., 2019), (7) this technology is useful for fabricating physical anatomical and pathological models or structures from Computed Tomography (CT) and Magnetic Resonance Images (MRI) that could be used as a tool for training surgeons (Liew et al., 2015), lastly (8) a 3D-printed arm cast has a significantly lower weight than the conventionally-manufactured cast (Fitzpatrick, 2017). Other 3D-printed medical and healthcare products, drugs, equipment, etc. are listed in Table 4.

3D printing in the Manufacturing Industry

3D printing provides major advancements and opportunities in the manufacturing sector. It offers a lot of advantages especially with small to medium batch manufacturing production, i.e., in design flexibility of complex parts and pieces, less mechanical joining of parts and materials that can improve process efficiency and prevent excessive material wastage, resulting in a lower total cost per production (Lim et al., 2016).

The increased availability of materials used to create 3D-printed objects has continued to build opportunities for various 3D printing applications in the manufacturing sector (Schniederjans, 2017). 3D printing is considered a transformative technology focused on manufacturing enterprises that have the potential to add up to a new type of industrial revolution (Bogue, 2013). An example of a revolutionary 3D-printed industrial spare part is a can filler valve for a beverage filler plant printed through direct metal laser sintering, i.e., the redesigned valve's weight is reduced to 35%. The AM process also eliminated the need to manufacture the entire can filler valve by printing it in a single piece which is a lot cheaper and leads to a shorter manufacturing time. Furthermore, a 3D-printed shower heads are now possible to be printed in moderate to mass quantities (Bogue, 2013). Other examples of industrial spare parts are listed in Table 5.

3D Printing Challenges in Various Industries

Despite the advantages that 3D printing can offer in spare parts production in various industries such as automotive, aeronautics, marine, medical, and manufacturing, some drawbacks and challenges still need to be addressed.

For instance, in the automotive industry, the low volume production of 3D-printed car components is not yet considered economical, as the profitability of businesses is usually directly proportional to the quantity of the products produced (Lim et al., 2016). It also implies that the speed of 3D printers and their bed size might lead to low volume spare parts production. In addition, some 3D prints must still go through post-processing and finishing processes after printing, which are time-consuming. Furthermore, the 3D printing knowledge and skills of employees and engineering graduates might still be insufficient (Thomas-Seale et al., 2018).

In the aeronautics industry, the challenge is ensuring the quality and efficiency of aircraft parts that usually require complicated manufacturing processes due to complexity and variability of functions. Since many components in an aircraft are load-bearing structures, testing and finding the mode of failure of each spare/component part is necessary before it can be used. However, due to the unusual environment to which aircrafts are usually subjected, preliminary study about in-situ testing restricts the 3D-printed spare parts from being used in non-structural and non-critical applications (Lim et al., 2016). 3D printing applications in aerospace also show some material limitations. The printer materials should not be in powder form as this can create a problem with the microgravity environment. The powder form produces uneven layers of print leading to poor print quality.

Like other industries, the maritime industry is not exempted from various challenges and drawbacks that must be addressed before the widespread adoption of 3D-printed parts in the marine applications. One of these challenges include material integrity as the properties of material vary due to printing layer by layer, thus, causing anisotropy which should be carefully considered for 3D printing of components for marine applications.

In the medical industry, it is evident that the primary challenge is the limitation of materials for 3D printers, such as the lack of commercially-available pharmaceutical-grade polymers containing Active Pharmaceutical Ingredients (API). In implantable medical devices such as the device used for ureteroscopy procedures, although it can be customized to the size of the patient's ureter with the use of 3D printing, it becomes difficult due to the lack of suitable printers and materials. Other specific challenges include the viability of cells and control of motility which can be improved by inserting a contraction force on the cell via anisotropic alignment (Jamróz et al., 2018).

While 3D printing has already emerged as a transforming technology with different applications in the manufacturing industry, more detailed information is still necessary to reach its full potential. To achieve the desired properties, such as density, strength, and hardness, which is essential in meeting the different application requirements, one should begin by analyzing the microstructure and characterizing the mechanical properties of the object produced via 3D printing (Lim et al., 2016). Recently, the authors reported on using the 3D printing technology to manufacture molds for injection molding applications. This is another direction that can be considered for mass production of spare parts (Dizon et al., 2019; Dizon et al., 2020).

Aside from the specific challenges encountered by each industry that have already been discussed, there are still common challenges in 3D printing spare parts across these various industries that need to be addressed. These include the inability to print on a larger scale and volume of materials, longer printing time, material availability, expensive printers, inaccurate actuation, and limited printing varieties of application in a single 3D printer (Bergsma et al., 2016). Other important 3D printing challenges include post-processing, material integrity, and intellectual property (Bergsma et al., 2016).

Future Outlook

Along with the progress and opportunities offered by Additive Manufacturing (AM), many industries are now realizing its potential impact on spare parts management. For instance, major companies are looking forward to producing end-use spare parts via AM to improve process efficiency by producing limited spare parts needed, thus, avoiding waste of resources and lowering total costs (Ukobitz and Faullant, 2021; *How 5 Major Automobile Manufacturers Use 3D Printing*, 2020).

The increasing number of available 3D printing materials, the ability to produce complicated geometry and lightweight spare parts, combined with the power to consolidate separate parts or

Table 4: 3D-Printed Spare Parts for the Medical Industry

Medical Spare Parts	Materials Used	Printer and 3D printing Technologies Used	Applications	Advantages and Disadvantages
Replacement parts for the WHO bioassay system/ kits (Tomlinson et al., 2019)	PLA	*Printing technologies* • Fused Deposition Modeling (FDM) *Printers* • Original Prusa i3 • MK3 and an MK3S (modified with a BuildTak print surface)	Replacement of parts of World Health Organization test (WHO bioassay kit) which commonly break, affecting its capacity to carry out resistance profiling.	*Advantages* • There is no recorded degradation of PLA after prolonged exposure times in commonly-used cleaning solutions • Replacement parts are identical to the original parts • PLA printed tubes and WHO acrylic tubes have no significant difference in mortality results. • Able to solve the problem on time.
Extra valves for ventilator devices (Sher, 2020; Robitzski, 2020)	Custom polyamide-based material	*Printing technologies* • Fused Deposition Modeling (FDM) • Stereolithography (SLA)	Patients are accompanied in breathing by a machine that uses a 3D-printed valve	Not Specified
Nanocellulose (Liang Ying and Sam Fong, 2021)	Not Specified	*Printing technologies* • Fused Deposition Modeling (FDM)	Wound dressing	*Advantages* • The 3D-printed nanocellulose does not support bacterial growth.
Human corneal epithelial cells (HCECs)/collagen/gelatin/ alginate hydrogel (Wu et al., 2016)	Not Specified	*Printing technologies* • Fused Deposition Modeling (FDM)	Tissue Engineering	*Advantages* • It has a hydrogel network, including a stable microporous structure in interconnected channels that can acquire more than 90% cell viability. • It also exhibited a greater cytokeratin 3 (CK3) and higher proliferation, which could mean that the developed technique may help enhance the alginate bioink system for 3D printing in tissue engineering.
Polylactic acid/ polycaprolactone/ hydroxyapatite (PLA/ PCL/HA) composites (Hassanajili et al.,2019)	Not Specified	*Printing technologies* • Negative mold Indirect 3D printing	Bone Tissue Engineering	*Advantages* • The composite scaffold has a PLA/PCL weight ratio of 70/30, which has obtained higher adjuvant properties in biocompatibility, viability, and osteo-induction.

Table 5: 3D-Printed Spare Parts for the Manufacturing Industry

Manufacturing Spare Parts	Materials used	Printer and 3D Printing Technologies Used	Applications	Advantages and Disadvantages
Legacy packaging arms in a pet food production line (*3D Printing Replacement Legacy Parts That Can No Longer Be Sourced*, 2019)	Onyx and isotropic reinforced carbon fiber	*Printing technologies* • Fused Deposition Modeling (FDM) *Printers* • Mark Two 3D printer	Replacement of packaging arms in a production line that is no longer available in the market malfunctions once every week and is a waste of time and costs for the company.	*Advantages* • The material used in the 3D printing of the replacement parts is onyx (characterized as having4 isotropic reinforced carbon fibers), a challenging and abrasion-resistant fabric. It is resilient to mechanical stresses and common machine chemicals. • Improves assembly and production line
Digitized Whirlpool's parts catalog (push button etc.) (*How 3D Printing Is Transforming the Spare Parts Industry [2021 Update]*, 2021)	ABS, ABS V0, PA12, a rubber-like resin, and PP-like resins	*Printing technologies* • Fused Deposition Modeling (FDM) • Stereolithography (SLA) • MultiJet Fusion (MJF)	Whirlpool adopts a digital inventory to optimize its spare parts system	*Advantages* • It increases the part availability in the market, leading to good customer service.
Can filler valve for beverage filler plant (*How 3D Printing Is Transforming the Spare Parts Industry [2021 Update]*, 2021)	Metal	*Printing technologies* • Direct Metal Laser Sintering • Direct Metal Laser Melting	3D printing metal spare parts for beverage filling plants	*Advantages* • It eliminated the procedures in manufacturing the entire can filler valve by printing it in single piece. • The redesigned valve reduced to 35% in weight • Cheaper and manufactured in shorter lead times.

components into one, are among the major advantages of AM that most industries are looking forward to. For instance, when 855 parts of an aircraft engine were reduced to 12 3D-printed components, the design weighed less, less fuel was used, and more power was produced (Bill Koenig, 2020).

In addition, the application of AM spare parts in the medical sector shows significant improvement; among these future trends include pathological organ models to aid surgical treatment, non-bioactive implants, biodegradable and bioactive scaffolds, and organ tissue printing (Holweg and Pil, 2004).

All these applications prove that 3D printing addresses some of the Sustainable Development Goals. For example, 3D printing of spare parts in the automotive, aerospace, maritime and manufacturing industries address, among others, SDG 1 (No Poverty), SDG 8 (Industry, Innovation and Infrastructure) and SDG 9 (Decent Work and Economic Growth); while 3D printing of parts for medical applications address, among others, SDG 3 Good Health and Well-being (Caldona et al., 2022).

IP Considerations

It is revolutionary to reproduce or create objects at the office or home. This has become increasingly easier with the cheap 3D scanners and free and easy-to-use CAD programs. High-speed internet and very powerful and affordable handheld devices and tools make creating and sharing designs altogether very easy. With 3D modeling and 3D printing, the digital object and its physical version continue to converge. These advances could work against it as companies might see 3D printing as a threat.

In the future, companies may propose that governments impose restrictions in light of their intellectual property rights and how 3D printing of spare parts affects their existing businesses. With the expiration of many patents on 3D printing technologies, it is now expected that 3D printers will become cheaper and better. Therefore, many companies producing spare/replacement parts will emerge and may then cause significant losses to Original Equipment Manufacturers (OEMs). These OEMs, in order to survive, might then ask authorities to apply some parts of the Digital Millennium Copyright Act (DMCA) for 3D printing.

SUMMARY

Additive Manufacturing or 3D printing has dramatically advanced in various industries as it can offer a lot of advantages to many practical applications. In spare parts production, 3D printing has helped various industries to be cost-efficient in terms of time and resources spent on an overestimated inventory. Aside from cost efficiency, 3D printing offers flexibility in design geometry, lightweighting and durability, rapid prototyping and printing-on-demand that can benefit the production of spare parts. These are the opportunities that led the manufacturing, automotive, aerospace, and maritime industries to adopt to this transformative technology. Furthermore, the increasing availability and continuous development of new materials used for 3D printers provide a wide perspective to the medical industry; it can directly be applied to implants, anatomical models, and other recent applications. However, there are challenges that should still be addressed.

ACKNOWLEDGEMENT

The authors would like to thank the support of the Department of Science and Technology—Philippine Council for Industry, Energy, and Emerging Technology Research and Development (DOST-PCIEERD) and the Research and Development Office of the Bataan Peninsula State University (BPSU).

CONFLICT OF INTEREST STATEMENT

The author(s) declare(s) that there is no conflict of interest.

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REFERENCES

3D Hubs. 3D printing. 2022. https://www.hubs.com/knowledge-base/3d-printing/ (accessed October 7, 2022).

3D printed car replacement parts are fueling the automotive revolution. 2020. https://www.3dspectratech.com/3d-printed-car-replacement-parts-are-fueling-the-automotive-revolution/.

3D printing replacement legacy parts that can no longer be sourced. 2019. https://www.additive-x.com/blog/3d-printing-replacement-legacy-parts-that-can-no-longer-be-sourced/ (accessed October 7, 2022).

3D printing: rising to the challenge in ship design, verdict media limited. 2015. https://www.ship-technology.com/features/feature3d-printing-rising-to-the-challenge-in-ship-design-4672912/ (accessed October 7, 2022).

Advincula RC, Dizon JRC, Caldona EB, et al. On the progress of 3D-printed hydrogels for tissue engineering. MRS Commun. 2021; 11:539-553.

Advincula RC, Dizon JRC, Chen Q, et al. Additive manufacturing for COVID-19: devices, materials, prospects, and challenges. MRS Commun. 2020; 10(3):413-427.

Ahmad H, Markina AA, Porotnikov MV, Ahmad F. A review of carbon fiber materials in automotive industry. IOP Conf Ser Mater Sci Eng. 2020; 971(3):032011.

Airbus gets on board with 3d printing. 2021. https://www.materialise.com/en/inspiration/cases/airbus-3d-printing (accessed October 7, 2022).

Attaran M. The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. Bus Horiz. 2017;60(5):677-688.

Autonomous Manufacturing. 2021. 10 exciting examples of 3d printing in the automotive industry in 2021. https://amfg.ai/2019/05/28/7-exciting-examples-of-3d-printing-in-the-automotive-industry/ (accessed October 7, 2022).

Barngrover C, Kastner R, Denewiler T, Mills G. The stingray AUV: a small and cost-effective solution for ecological monitoring. *Oceans'11 Mts/Ieee Kona; 2011: 1-8.*

Bayramoğlu K, Deniz KK, Yilmaz S, Göksu B, Murato B. Utilization of 3d printing technologies in marine applications; 2019.

Bergsma J, van der Zalm M, Pruyn J, Bergsma JM, Pruyn JFJ. 3D-printing and the maritime construction sector. 2016.

Bogue R. 3D printing: The dawn of a new era in manufacturing? Assembly Automation. 2013; 33(4):307-311.

Boissonneault T. Carbon and Ford showcase 3D printed end-use parts at NAIAS. 2019. https://www.3dprintingmedia.network/carbon-ford-3d-printed-automotive-naias/ (accessed October 7, 2022).

Brown BB. The RCSA. Characteristics of demand for aircraft spare parts. RAND. 1956; 1-39.

Campbell T, Williams C, Ivanova O, Garrett B. Strategic Foresight Report. Atlantic Council. 2012; 01:3-7.

Can 3d printing use metal? 2022. https://www.twi-global.com/technical-knowledge/faqs/what-is-3d-printing/can-3d-printing-use-metal#Conclusion (accessed October 7, 2022).

Caldona E, Dizon JRC, Espera A, Advincula RC, On the Economic, Environmental, and Sustainability Aspects of 3D Printing toward a Cyclic Economy. In: Boul PJ, ed. Energy Transition: Climate Action and Circularity. Washington, DC: ACS Publications, 2022: 507-525. https://doi.org/10.1021/bk-2022-1412.ch011

Chia HN, Wu BM. Recent advances in 3D printing of biomaterials. J Biol Eng. 2015;9(1):1-14.

Choonara YE, du Toit LC, Kumar P, Kondiah PPD, Pillay V. 3D-printing and the effect on medical costs: a new era? Expert Rev Pharmacoecon Outcomes Res. 2016; 16(1):23-32.

Creative Mechanisms. Everything you need to know about polypropylene (pp) plastic. 2016. https://www.creativemechanisms.com/blog/all-about-polypropylene-pp-plastic (accessed October 7, 2022).

Crivello JV, Reichmanis E. Photopolymer materials and processes for advanced technologies. Chemistry of Materials. 2014; 26(1):533-548.

D'Epagnier KP, Chung HL, Stanway MJ, Kimball RW. An open-source parametric propeller design tool. 2007; 1-8.

Davies S. Additive is a lighthouse: Siemens mobility on the growing importance of 3D printing in the rail sector. 2020. https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/siemens-mobility-growing-importance-3d-printing-rail/ (accessed October 7, 2022).

De Leon AC, Chen Q, Palaganas NB, Palaganas JO, Manapat J, Advincula RC. High performance polymer nanocomposites for additive manufacturing applications. React Funct Polym. 2016; 103:141-155.

De Mori A, Fernández MP, Blunn G, Tozzi G, Roldo M. 3D printing and electrospinning of composite hydrogels for cartilage and bone tissue engineering. Polymers (Basel). 2018;10(3).

Diego JR, Martinez DWC, Robles GS, Dizon JRC. Development of smartphone-controlled hand and arm exoskeleton for persons with disability. De Gruyter. 2021:161-170.

Dizon JRC, Espera AH, Chen Q, Advincula RC. Mechanical characterization of 3D-printed polymers. Additive Manufacturing. 2017; 20: 44-67.

Dizon JRC, Gache CCL, Cascolan HMS, Cancino LT, Advincula RC. Post-processing of 3D-printed polymers. Technologies (Basel). Published online 2021.

Dizon JRC, Valino AD, Souza LR, Espera AH, Chen Q, Advincula RC. 3D printed injection molds using various 3d printing technologies. Materials Science Forum. 2020; 1005:150-156.

Dizon JRC, Valino AD, Souza LR, Espera AH, Chen Q, Advincula RC. Three-dimensional-printed molds and materials for injection molding and rapid tooling applications. MRS Commun. 2019;9(4):1267-1283.

Ee LY, Yau Li SF. Recent advances in 3D printing of nanocellulose: structure, preparation, and application prospects. *Nanoscale Advances*. 2021; *3*(5), 1167–1208.

Eggenberger T, Oettmeier K, Hofmann E. Additive manufacturing in automotive spare parts supply chains – a conceptual scenario analysis of possible effects. International Conference on Additive Manufacturing in Products and Applications. 2017.

Espera AH, Valino AD, Palaganas JO, Souza L, Chen Q, Advincula RC, 3D Printing of a Robust Polyamide-12-Carbon Black Composite via Selective Laser Sintering: Thermal and Electrical Conductivity, Macromol. Mater. Eng. 2019; 304(4): 1800718.

Espera AH, Dizon JRC, Chen Q, Advincula RC. 3D-printing and advanced manufacturing for electronics. Progress in Additive Manufacturing. 2019;4(3):245-267.

Fitzpatrick PA. Design of a patient specific, 3d printed arm cast. KnE Engineering. 2017; 2(2):135.

Ford Motor Company. Ford develops 3d-printed locking wheel nuts to thwart thieves. 2022. https://corporate.ford.com/articles/products/3d-printed-locking-wheel-nuts.html (accessed October 7, 2022).

Gardner N. Introduction to 3D printing in the maritime industry. 2021. https://thetius.com/3d-printing-in-the-maritime-industry/ (accessed October 7, 2022).

Garrett B. 3D printing: New economic paradigms and strategic shifts. Glob Policy. 2014;5(1):70-75.

Gasman L. Additive aerospace considered as a business. Additive Manufacturing for the Aerospace Industry, Elsevier 2019; 15:327-340.

Goodridge RD, Tuck CJ, Hague RJM. Laser sintering of polyamides and other polymers. Prog Mater Sci. 2012; 57(2):229-267.

Grant, M. J., and Booth, A. (2009). A typology of reviews: an analysis of 14 review types and associated methodologies. *Health Information and Libraries Journal*, *26*(2), 91–108.

Haleem A, Javaid M. 3D printed medical parts with different materials using additive manufacturing. Clin Epidemiol Glob Health. 2020; 8(1):215-223.

Hassanajili S, Karami-Pour A, Oryan A, Talaei-Khozani T. Preparation and characterization of PLA/PCL/HA composite scaffolds using indirect 3D printing for bone tissue engineering. Materials Science and Engineering: C 2019; 104:109960.

Holweg Matthias, Pil FK. The second century: reconnecting customer and value chain through build-to-order: moving beyond mass and lean production in the auto industry. MIT Press; 2004.

How 3d printing is transforming the spare parts industry. 2021. https://amfg.ai/2018/05/29/3d-printing-transforming-spare-parts-industry/ (accessed October 7, 2022).

How 5 major automobile manufacturers use 3d printing. 2020. https://www.wevolver.com/article/how.5.major.automobile.manufacturers.use.3d.printing (accessed October 7, 2022).

Jamróz W, Szafraniec J, Kurek M, Jachowicz R. 3D printing in pharmaceutical and medical applications. Pharm Res. 2018; 35(9): Article 176.

Jiang R, Kleer R, Piller FT. Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030. Technol Forecast Soc Change. 2017; 117:84-97.

Jin FL, Li X, Park SJ. Synthesis and application of epoxy resins: A review. Journal of Industrial and Engineering Chemistry. 2015; 29:1-11.

Joshi SC, Sheikh AA. 3D printing in aerospace and its long-term sustainability. 2015;10(4):0-90.

Kalender M, Kilic SE, Ersoy S, Bozkurt Y, Salman S. Additive manufacturing and 3D printer technology in aerospace industry. Proceedings of 9th International Conference, RAST; 2019:689-695.

Karami-Pour A, Oryan A, Talaei-Khozani T. Preparation and characterization of PLA/PCL/HA composite scaffolds using indirect 3D printing for bone tissue engineering. *Materials Science and Engineering:* 2019; *104*, 109960.

Kostidi E, Nikitakos N. Additive manufacturing of spare parts in the maritime industry in the digital era. IAME 2019 Conference. 2019.

Kostidi E, Nikitakos N. Exploring the potential of 3D printing of the spare parts supply chain in the maritime industry. Safety of Sea Transportation - Proceedings of the International Conference on Marine Navigation and Safety of Sea Transportation, TRANSNAV 2017:171-178.

Kostidi E, Nikitakos N. Exploring the potential of 3D printing of the spare parts supply chain in the maritime industry. In: Safety of Sea Transportation - Proceedings of the International Conference on Marine Navigation and Safety of Sea Transportation, TRANSNAV 2017. CRC Press/Balkema; 2017: 171-178.

Kostidi E, Nikitakos N. Is it time for the maritime industry to embrace 3d printed spare parts? transnav, the international journal on marine navigation and safety of sea transportation. 2018; 12(3):557-564.

Kotta S, Nair A, Alsabeelah N. 3d printing technology in drug delivery: recent progress and application. Curr Pharm Des. 2018; 24(42):5039-5048.

Large scale 3d printing. 2022. https://3dprinting.com/3dprinters/best-large-scale-fdm-fff-3d-printers-big-enough-to-3d-print-furniture/ (accessed October 7, 2022).

Lecklider T. 2016 3D printing drives automotive innovation. https://www.evaluationengineering.com/test-issues-techniques/technology/3d-printing/article/13014908/3d-printing-drives-automotive-innovation (accessed October 6, 2022).

Liew Y, Beveridge E, Demetriades AK, Hughes MA. 3D printing of patient-specific anatomy: A tool to improve patient consent and enhance imaging interpretation by trainees. Br J Neurosurg. 2015; 29(5):712-714.

Lim CWJ, Le KQ, Lu Q, Wong CH. An Overview of 3-D Printing in Manufacturing, Aerospace, and Automotive Industries. IEEE Potentials. 2016; 35(4):18-22.

Liu Z, Zhang L, Yu E, et al. Modification of glass fiber surface and glass fiber reinforced polymer composites challenges and opportunities: from organic chemistry perspective. Curr Org Chem. 2015; 19(11):991-1010.

Lupton D. 3d printing technologies: social perspectives. SSRN Electronic Journal. Published online 2017:1-6.

M. Rokonuzzaman. 3D printing and spare parts value chain. 2020. https://thefinancialexpress.com.bd/public/views/ (accessed October 7, 2022).

Ma GW, Wang L, Ju Y. State-of-the-art of 3D printing technology of cementitious material—an emerging technique for construction. Sci China Technol Sci. 2018;61(4):475-495.

Martinez DW, Espino MT, Cascolan HM, Crisostomo JL, Dizon JRC. A comprehensive review on the application of 3d printing in the aerospace industry. Key Eng Mater. 2022; 913:27-34.

Metal 3d printing. 2022. https://www.materialise.com/en/manufacturing/3d-printing-technology/metal-3d-printing (accessed October 7, 2022).

Metal powders for additive manufacturing. 2022. https://www.ge.com/additive/additive-manufacturing/information/metal-additive-manufacturing-materials (accessed October 7, 2022)

Mir TA, Nakamura M.ional bioprinting: toward the era of manufacturing human organs as spare parts for healthcare and medicine. Tissue Eng Part B Rev. 2017; 23(3):245-256.

Muir M, Haddud A. Additive manufacturing in the mechanical engineering and medical industries spare parts supply chain. Journal of Manufacturing Technology Management. 2018; 29(2):372-397.

Mullen D. Porshe launches 3d-printed customisable body form bucket seat. 2021. https://www.driving.co.uk/news/technology/porsche-3d-printed-seat/ (accessed October 7, 2022).

NASA. Industry test additively manufactured rocket engine injector. NASA-rocket-injector. 2013. https://www.nasa.gov/press/2013/july/nasa-industry-test-additively-manufactured-rocket-engine-injector-0/#.Yz_lMXZBy3A (accessed October 7, 2022).

Ngo TD, Kashani A, Imbalzano G, Nguyen KTQ, Hui D. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. Compos B Eng. 2018; 143:172-196.

Nichols MR. How does the automotive industry benefit from 3D metal printing? Metal Powder Report. 2019; 74(5):257-258.

Nickels L. AM and aerospace: An ideal combination. Metal Powder Report. 2015;70(6):300-303.

OECD, The next production revolution: implications for governments and business, OECD Publishing, Paris, 2017.

Peels J. Tyr3D: 3D Printing Replacement Car Parts in the Backside of Ireland. 2017. https://3dprint.com/187735/tyr3d-replacement-car-parts/ (accessed October 7, 2022).

Peters EN. Plastics: thermoplastics, thermosets, and elastomers. in: handbook of materials selection. John Wiley and Sons, Inc.; :335-355.

Pierrakakis K, Gkritzali CD, Kandias M, Gritzalis D. 3D printing: a paradigm shifts in political economy. 65th International Studies Association's Annual Convention. 2015; 18-21.

Rainey K. Building the future: space station crew 3-d prints first student- designed tool in space. 2016:1-5. https://www.nasa.gov/mission_pages/station/research/news/ multipurpose_precision_maintenance_tool (accessed October 7, 2022).

Rajak D, Pagar D, Menezes P, Linul E. Fiber-reinforced polymer composites: manufacturing, properties, and applications. Polymers (Basel). 2019; 11(10):1667.

Ramya A, Vanapalli SL. 3D printing technologies in various applications. International Journal of Mechanical Engineering and Technology. 2016;7(3):396-409.

Ratto, M., and Ree R. Materializing information: 3D printing and social change. First Monday. 2012;(17(7)).

Ridol A, Bartolini F, Monni N, et al. SAUC-E 2012-UNIFI team-turtle vehicle. 2012. https://www.academia.edu/20925536/SAUC_E_2012_UNIFI_Team_Turtle_vehicle (accessed October 7, 2022).

Robitzski D. An overwhelmed italian hospital is 3d printing replacement parts. 2020. https://futurism.com/neoscope/overwhelmed-italian-hospital-3d-printing-parts (accessed October 7, 2022).

Salmi M, Akmal JS, Pei E, Wolff J, Jaribion A, Khajavi SH. 3D printing in COVID-19: productivity estimation of the most promising open-source solutions in emergency situations. Applied Sciences (Switzerland). 2020; 10(11):1-15.

Sam Davies. 3D printed replacement parts service in operation. Published 2019. https://www.tctmagazine.com/ (accessed August, 2022).

Sarvankar SG, Yewale SN. Additive manufacturing in automobile industry. international journal of research in aeronautical and mechanical engineering. 2019; 7(4):01-10.

Savastano M, Amendola C, D'Ascenzo F, Massaroni E. 3-D printing in the spare parts supply chain: An explorative study in the automotive industry. Lecture Notes in Information Systems and Organisation. 2016; 18:153-170.

Schiller GJ. Additive manufacturing for aerospace. *IEEE Aerospace Conference. 2015; 1-8.*

Schmitt M, Mehta RM, Kim IY. Additive manufacturing infill optimization for automotive 3D-printed ABS components. 2020; 89-99.

Schniederjans DG. Adoption of 3D-printing technologies in manufacturing: A survey analysis. Int J Prod Econ. 2017; 183:287-298.

Schwaar C. 2022. WAAM. What is wire arc additive manufacturing? https://all3dp.com/1/waam-what-is-wire-arc-additive-manufacturing/ (accessed October 7, 2022).

Shahrubudin N, Lee TC, Ramlan R. An overview on 3D printing technology: technological, materials, and applications. Procedia Manufacturing Elsevier. 2019; 35:1286-1296.

Sher D. Italian hospital saves Covid-19 patients' lives by 3D printing valves for reanimation devices. 3D Printing Media Network. 2020. https://www.3dprintingmedia.network/covid-19-3d-printed-valve-for-reanimation-device/ (accessed October 7, 2022).

Standard terminology for additive manufacturing technologies. Published online 2013.https://web.mit.edu/2.810/www/files/readings/AdditiveManufacturingTerminology.pdf (accessed October 7, 2022).

Strickland JD. Applications of additive manufacturing in the marine industry. PRADS. Proceedings of the 13th International Symposium on PRActical Design of Ships and Other Floating Structures. 2016.

Stuart H, Wang S, Gardineer B, Christensen D, Aukes D, Cutkosky M. Robotics and automation (ICRA). IEEE International Conference; 2014: 6822.

Taş ŞO, Şener B. The use of additive manufacturing in maritime industry. international journal of engineering trends and technology. 2019; 67(6):47-51.

Thomas-Seale LEJ, Kirkman-Brown JC, Attallah MM, Espino DM, Shepherd DET. The barriers to the progression of additive manufacture: perspectives from UK industry. Int J Prod Econ. 2018; 198:104-118.

Tijing L, Dizon JR, Cruz Jr. G. 3D-printed absorbers for solar-driven interfacial water evaporation: a mini-review. advance sustainable science, engineering and technology. 2021;3(1):0210103.

Tijing LD, Dizon JRC, Ibrahim I, Nisay ARN, Shon HK, Advincula RC. 3D printing for membrane separation, desalination and water treatment. Appl Mater Today. 2020; 18:100486.

Tomlinson S, Carrington Yates H, Oruni A, et al. Open-source 3D printable replacement parts for the WHO insecticide susceptibility bioassay system. Parasit Vectors. 2019; 12(1):1-7.

TPU material. 2020. https://tractus3d.com/materials/tpu/ (accessed October 7, 2022).

Tuazon BJ, Custodio NA, Basuel R, Delos Reyes LA, Dizon JR. 3D printing technology and materials for automotive application: a mini-review. Key Engineering Materials Trans Tech Publications, Ltd. 2022; 913: 3.

Ukobitz D, Faullant R. Leveraging 3d printing technologies: The Case of Mexico's footwear industry: Mexico's fashion footwear industry serves as an example of how companies in traditional sectors that adopt 3D printing can realize benefits along their value chain. Research Technology Management. 2021;64(2):20-30.

Ultimate 3D printing materials guide. 2022. https://www.simplify3d.com/support/materials-guide/ (accessed October 7, 2022).

Valino AD, Dizon JRC, Espera AH, Chen Q, Messman J, Advincula RC. Advances in 3D printing of thermoplastic polymer composites and nanocomposites. Prog Polym Sci. 2019; 98:101162.

Van der Zalm M. 2017. On the assessment of additive manufacturing potential in the maritime construction sector: the effect on ship design. http://resolver.tudelft.nl/uuid:c16662b2-0925-449f-8368-da8ad156eb26 (accessed October 6, 2022).

Ventola CL. Medical applications for 3d printing: current and projected uses. Pharmacy and Therapeutics. 2014; 39(10):704-11.

Vijayenthiran V. Porsche starts offering 3D-printed seats. https://www.motorauthority.com/news/1127483_porsche-starts-offering-3d-printed-seats (accessed October 7, 2022).

Vujović I, Kuzmanić I, Kulenović Z, Maleš N, Navy C. Additive manufacturing of spare parts in maritime industry-technology transfer in mariner education. 21st International Research/Expert Conference "Trends in the Development of Machinery and Associated Technology." 2018; 277-280.

What's the difference between PLA and ABS? 2022. https://zmorph3d.com/blog/difference-between-pla-abs (accessed October 7, 2022).

Wu Z, Su X, Xu Y, Kong B, Sun W, Mi S. Bioprinting three-dimensional cell-laden tissue constructs with controllable degradation. *Scientific Reports*. 2016; *6*(1), 24474.