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REVIEW ARTICLE

Large-format additive manufacturing of polymer extrusion-based deposition systems: review and applications

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Abstract

Additive manufacturing (AM) of polymer large parts is a technological research area with great growth potential if the main barriers to its implementation are successfully addressed. In this research, a review of large-format AM (LFAM) processes for polymers is presented, followed by market research concerning the identification of large-format polymer commercial printers. An overview was performed covering the current LFAM systems configurations and their control aspects. The design and modelling approaches related with the fabrication of polymer large parts by AM, and the materials currently being applied and under development, were described. Finally, a summary of LFAM applications with a focus in the Transportation, Academic, Construction and Energy sectors, was presented. The current main advances in the LFAM of polymers are linked with the possibility of producing large parts in a faster, cheaper, and reliable way. The market research analysis concerning results for all AM families involving polymer materials reveals that, currently, the material extrusion AM process family is potentially the most suitable to produce large parts, with a significant number of applications attesting its capability to produce such large-format components.

Keywords Material extrusion · LFAM · Big area · Reinforced thermoplastic filaments · Market research

1 Introduction

Commonly denoted as 3D printing, additive manufacturing (AM) is defined by the standard ISO-ASTM 52,900:2021 as "the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" [1]. By promoting a revolution in the way products are designed, manufactured, and distributed to end users, AM-related technologies have gained significant academic and industrial interest, due to their ability to create complex geometries with customizable material properties [2, 3]. The global interest on AM is revealed by the growing rate of both 3D printing systems sales and market value, that grew 27.4% over the previous 10 years, to nearly $12.8 billion by the end of 2020 [4]. Polymers are the most used 3D printed materials and there are more polymer 3D printers in use than any other technology. In 2019, 72% of the companies using AM were using polymer systems, compared to 49% metal systems [5]. Given the substantial opportunities in polymer AM production, predictions expect it to generate $24 billion in revenues in 2024, a number that includes sales of hardware, materials and 3D-printed parts combined [6]. On the other hand, the same reports refer that material extrusion technologies like Fused Filament Fabrication (FFF) have already generated the most revenue among professional environments in 2019 [6].

Several reviews have been published for AM systems, materials, and applications in the last years, demonstrating the interest of the scientific community. Since 2018, there are general reviews [3–8], more applied with applications in

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construction [9, 10], medical [11], aerospace [12, 13], and automotive [14]. There are several reviews concerning materials [15–22], equipment and systems [23, 24] and optimization of parts for AM [25–29]. Reviews on the use of AM in Industry 4.0 [30] and on economics aspects of AM [31, 32].

The issue of large part printing with polymers is so important that Tiwary et al. published a review on post-processing to join parts and circumvent build volume limitation of the FFF process [33]. In 2015, a first review was produced reporting the results of LFAM polymer systems [34] and in 2020, two reviews focused on LFAM with polymers were published with data collected from 2000 to 2020 [35, 36].

In this work, a state of the art of additively manufactured polymer large parts is conducted through a bibliographic and market research, aiming to guide research directions to improve the performance of systems and behavior of these large-format parts.

This paper is organized as follows, first, a general review of 3D printing with polymers is presented in Sect. 2. Market research concerning large-format polymer commercial printers available with their main characteristics are exhibited. An overview covering current system configurations, workflow, constraints and their control aspects and mitigation is detailed after. Design and modelling approaches related with large-format parts and their thermal behavior, and materials for large part 3D printing finishes this section. Section 3 introduces current applications in the fields the Transportation, Academic, Construction and Energy sectors. Several examples of large parts applications and it benefits, and limitations are presented. Section 4 will resume some challenges and enumerate some opportunities for LFAM, and Sect. 5 will present conclusions and future work.

The current main advances in the large-format system technologies are naturally linked with the possibility of producing large parts in a faster, cheaper, and reliable way. In this review, the authors accept that issues and challenges for both large format and "normal format" that are the same should be addressed in another work and therefore, the author assume only the differences and the issues of LFAM of polymers. For example, there are issues and challenges with software regarding slicing and trajectories of deposition heads to increase the quality of the finished part, but in this review, the authors focus on the issues for LFAM.

2 Large-format polymer extrusion-based deposition systems

In this section, first, it is presented several issues associated with large parts 3D printing of polymeric parts, namely the AM processes for polymers, followed by systems architectures and configurations, process planning and materials for large parts.

In this work, the size of polymer parts produced by AM are classified according to the following terminology: small format AM for parts with a volume less than 1 m^3 and LFAM for parts with a volume greater than 1 m^3. Within the LFAM classification, medium size AM (MSAM) machines with volumes between 1 m^3 and 7 m^3, and high size AM machines (HSAM) for parts larger than 7 m^3 were also considered.

2.1 AM processes for polymers

To establish a picture of the state of the art regarding the AM of polymer large parts, market research was carried out to determine which equipment (for each AM family) allows to obtain larger polymeric components. For each AM family, the equipment's are compared considering their main technical characteristics, and a general outlook between the different families is presented. This search was done without any contact with companies or other research groups. It is intended to show maximum dimensions for models built in the last years.

2.1.1 Material jetting

Material jetting printers are characterized by their excellent accuracy and precision, allowing the printing of parts with various colors and materials, in a process that requires little concern with support structures [37]. Its characteristic good accuracy and resolution are usually dependent on a limited volume and relative speed, which inevitably imply that printers are typically expensive. From our market research, the model Mimaki 3DGD-1800 from Mimaki is the one which allows to print larger parts (up to 2.90 m^3) [38], with a layer resolution of 800 µm. The only reported value for its building speed is 350 mm/hour (vertical direction), which is a high speed, when compared with the building rates of other printers of this AM process family.

2.1.2 Powder bed fusion

Powder bed fusion printers are limited in size by the available volume of the powder bed [39], from all studied models, the TPM3D S800DL from TPM3D has a maximum build volume of 0.29 m^3 [40]. Even so, the printing process is time consuming since the volume build rates (10–25 mm^3/h) are low. For instance, considering a volume build rate of 25 mm^3/h, the required time to print a volume of 0.29 m^3 will be almost one week. The price of equipment and consumables is also high when compared with other AM technologies.

2.1.3 Binder jetting

A key advantage of binder jetting over other AM processes is that bonding occurs at room temperature. This means that dimensional distortions associated with thermal effects are not a problem. As a result, the build volume of binder jetting machines is amongst the largest among AM technologies (up to $2200 \times 1200 \times 600$ mm, roughly 1.6 m^3) [41]. These large machines are generally used to produce sand-casting molds. Metal and polymer binder jetting systems typically have smaller build volumes (up to $1000 \times 600 \times 500$, 0.3 m^3) for the polymer printer Voxeljet AG VX1000 from Voxeljet AG [42]. Typical layer height depends on the material, which for polymers will be around 100 µm.

2.1.4 Vat polymerization

The build volume of vat polymerization systems is primarily defined by the vat that contains the photopolymerizable resin. In some systems the produced part can be larger than the photopolymer vat, since the part is produced using a bottom-up approach. In this configuration the optical source is projected on the bottom of the vat. The print starts by lowering the build platform to touch the bottom of the resin-filled vat, then moving upward the height of one layer and successively adding new layers to the object [43]. This bottom-up approach allows to obtain parts up to 2.1 m long on the Materialize machine [44]. Compared to traditional vat polymerization, these larger systems can provide unique parts (without assemblies), which can increase their mechanical performance, commonly identified as one of the downsides of vat polymerization technology.

2.1.5 Material extrusion

ASTM defines material extrusion, as “AM process in which material is selectively dispensed through a nozzle or orifice” [1]. Concerning polymers extrusion, the process can be done with thermoplastic-based materials, where the raw materials are either in the form of filament (FFF) or pellets (FGF, fused granular fabrication), both processes involve the melting of raw materials on a vertical extrusion system. An extrusion system is a system constituted by a feeder, a hot end, and a nozzle. The function of the feeder is to place filament/pellets into the hot end. The hot end will melt the polymer and guide the melted polymer to the nozzle, that is responsible to define the diameter of melted material to be deposited. The polymer extrusion process can also be performed with thermosets (without melting), using an extrusion head that combines resin and hardener during deposition [45, 46]. In general, the relationship between nozzle diameter, head speed and material feed rate are coordinated such that material deposition is precise, creating the desire product layer by layer [47].

Within all AM process families, FFF has become one of the most widely used AM processes in the industry for functional prototypes and low volume production series, using polymers such as Acrylonitrile Butadiene Styrene (ABS), Polycarbonate (PC) or Polylactic Acid (PLA), with some restrictions regarding mechanical performance. To increase the mechanical performance (strength, stiffness, and creep) of parts obtained by FFF, engineering plastics like polyphenylsulfone (PPSU), polyetherimide (PEI) and polyether ether ketone (PEEK) are under continuous development. These materials offer improved specific bulk properties but are often limited by defects inherent to FFF technique, namely, a layered structure with difficult to predict porosities between adjacent rasters, and low inter-layer adhesion.

From our market research, the commercially available material extrusion printers with larger volumes are the Jupiter from ATMAT using filaments [48], and the LSAM 1540 from Thermwood using pellets [49], with building volumes of 2.0 and 84.6 m^3, respectively. The Jupiter model from ATMAT is equipped with two printing heads specifically designed for large-format production and owns a granite heated bead to ensure a stable operation. The Jupiter printer also had a heated chamber and can deposit up to 0.5 kg of material per hour. The LSAM 1540 manufacturing system from Thermwood has a proprietary print head extruder called “MELT CORE”. This new design uses a servo-controlled plastic extruder with a plasticizing screw to heat and soften the polymer. After the bead deposition, the bead is compressed through a system based on a servo-controlled compression wheel, that flattens and fuses each new printed layer to existing layers. The LSAM 1540 printer from Thermwood has a maximum printing temperature of 450 ºC and can deposit between 91 and 227 kg of material per hour, using 40- and 60-mm print heads, respectively. The LSAM 1540 printer can also be used with the “Vertical Layer Print” set-up. In the “Vertical Layer Print” set-up parts are printed along the length of the print bed, with the layer stack direction along the length of the part. The LSAM 1540 printer does this by adding a second moving table, mounted perpendicular to the main fixed horizontal table. Thermwood state that the employed “controlled cooling” print technology minimizes sag, which is a common problem in thermoplastics 3D printing. With the “Vertical Layer Print” set-up, the LSAM 1540 printer can print parts with a length up to 12 m.

After the market research analysis, results for all AM families involving polymer materials reveal that, currently, the AM process family most suitable to produce LFAM parts is most likely based in material extrusion configurations, mostly due to the capability of producing larger parts with low costs, Table 1.

Table 1 Characteristics of the largest polymer commercial printers by AM family

Am family	Brand/model	Dimensions (mm)	Volume (m^3)	Layer height (µm)
Material jetting	Mimak/3DGD-1800	1450 × 1110 × 1800	2.90	800
Powder bed fusion	TPM3D/S800DL	800 × 800 × 450	0.29	60–300
Binder jetting	Voxeljet/AG VX1000	1000 × 600 × 500	0.30	150 or 300
Vat polymerization	Materialize/	2100 × 800 × 700	2.1	100
Material extrusion [filament]	ATMAT/Jupiter	2000 × 1000 × 1000	2.00	200*
Material extrusion [pellets]	Thermwood/LSAM 1540	12 190 × 4570 × 1520	84.60	5 000*

*Minimum

Besides all of its benefits, conventional material extrusion imposes fundamental limitations on speed, and scale of parts [50–52]. As a way to overcome the limitations of scale, LFAM methods such as medium size AM (MSAM) [53] and high size AM (HSAM) [54], with build volumes ranging from 1 to 7 m^3 in MSAM and higher than 7 m^3 on HSAM, have received a lot of attention in the last years.

Also, a limitation of the conventional FFF process is the rate of deposition that is constraint by the head speed, acceleration, and extrusion diameter (0.1–0.5 mm), which limits the deposition rates to less than 0.5 kg/h, on printers usually with small build volumes (< 1 m^3). LFAM methods can employ large extrusion head diameters (0.5– 4 mm in MSAM and 4–7.6 mm in BSAM) that are commonly feed by polymer pellets [55, 56] instead of filaments, which beyond increasing the deposition rates (to 0.5–4 kg/h in MSAM and 4–50 kg/h in HSAM) can also represent a reduction in costs of raw materials in more than one order of magnitude. LFAM surges as a solution to manufacture large parts while avoiding joining/welding of multiple parts, as extensively addressed in a research review by Tiwary et al. [33].

Tiwart et al. stated that their paper is the first literature review related with joining or welding of FFF 3D printed parts to obtain a bigger volume 3D printed component. This element of welding after fabrication of smaller components is a competition for systems capable of 3D printing of volumes directly. On this review, different joining techniques including adhesive bonding, mechanical interlocking, use of fasteners, LFAM and welding are presented with particular emphasis on the welding of 3D printed parts. The authors describe the procedures for applying the above referred joining/welding techniques, the correspondent advantages and limitations and present the challenges and future research direction in the context of 3D printed parts.

When evaluating processing costs, the energy requirements of LFAM methods (4×10^6 J/kg), are one order of magnitude lower than the one reported for the small-scale AM (4.1×10^7 J/kg) [52], due to several factors, including the removal of the heated chamber [32]. The elimination of the heating chamber in LFAM systems, brings associated problems of part warping during the cooling process. If unoptimized, the material's anisotropic shrinkage and nonlinear compression characteristics cause severe delamination, cross-sectional tapering, and warpage [57, 58], and also increasing the risk of sagging structures [59]. One repeatedly reported solution to minimize warping, is the use of thermoplastics reinforced with small fibres [60–63]. Reinforced thermoplastics have an average thermal expansion coefficient one order of magnitude smaller than the unreinforced thermoplastics. An alternative approach is the utilization of thermoset materials using an extrusion head that combines resin and hardener during deposition [45, 46]. In LFAM, time is commonly compromised or, using larger extrusion widths, the tendency is a decrease in resolution and a consequent decline in part surface finish [64, 65]. Therefore, the lack of print resolution and extruder flowrate control, characteristic of HSAM systems, can lead to potentially significant geometric deviations in the printed part [55, 58, 66].

On the last years, several new models of LFAM printers were introduced on the market. The website aniwwa.com reports 30 LFAM printer's models with size higher than 1 m^3. The prices from models with size higher than 1 m^3, vary from 11 500 to up to $ 450,000 (for high-performance polymer). More than half of these models were released in 2021 and 2022. The complete list of LFAM printers can be found in Annex I.

For comparison, the most common process characteristics of small and LFAM methods are displayed in Table 2.

2.2 Systems configurations for extrusion systems

The manufacturing of larger parts certainly implies increased complexity concerning types of system configuration and their respective automation and control mechanisms. In a quest to address this issue, various new machine concepts have arisen with these solutions

Table 2 The main process characteristics commonly associated with small-scale and LFAM methods

	Small format AM	LFAM	
		MSAM	HSAM
Build volumes (m^3)	< 1	1–7	> 7
Deposition rates (kg/h)	< 0.5	0.5–4	4–50
Cost ($/Kg)	100–200	4–10	4–10
Raw material	Filament	Pellets	Pellets
Extruder diameter (mm)	0.1–1	0.5–4 Variable	4–7.6 Variable
Number of extruders	Single	Single Multiple	Single Multiple
Energy requirements (J/kg)	High	Low	Low
Surface quality	Medium	Low	Low
Motion	Cartesian, polar	Cartesian, polar	*xy* table and *z* axis, robotic arms
Bonding	Hot air plastic welding, Ultrasonic spot welding	Plastic seams	Plastic seams
Slicing methods	Established	New	New
Materials	Thermoplastics and thermoplastics reinforced with short fibers	Thermoplastics reinforced with short fibers	Thermoplastics reinforced with short-fibers and thermosets

incorporating mechanisms such as robotic arms [67–69], pellets [55, 70, 71], multiple and adaptable nozzle sizes [64, 65], multiple extrusion heads/modular and cooperative manufacturing [67, 72–79].

2.2.1 Robotic arms

Felsch's et al. [68] robotic arm system is an example that combines flexible and cost-effective industrial robots, with the authors making an evaluation of the manufacturing technology, the system architecture, and the motion planning. An articulating arm was also designed and implemented by Jasiel Minjares [69] into a BAAM machine.

2.2.2 Pellets

Some authors approach to large extrusion systems starts by replacing the most common filament material by a pellet material feed [70, 71]. Most often, this modification will impose the need to incorporate a servo driven screw extruder, increasing machine complexity. Even so, when compared with filament extrusion, pellets solutions usually imply that material cost is decreased, and other problems such as filament runout is no longer an issue. In addition, pellet extrusion technology can increase the process rate, by more than 2 orders of magnitude, and decreases the electricity requirement per kg by about 2 orders of magnitude when compared to with filament extrusion technology [52]. A research by Zhiyuan Wang et al. shows that, for BAAM pellet extrusion, the process efficiency and deposition quality can be increased by using a variable pitch and progressive diameter screw [55].

2.2.3 Multiple and adaptable nozzles

Multiple and adaptable nozzles can be selectively used in different build areas of a part aiming at increasing surface quality of BAAM parts without significantly increasing print time. Chesser et al. explored the application of variable extrusion head diameter, through a poppet nozzle selector, achieving variable deposition rates in different regions of a part [64]. Using a proof-of-concept machine, Paritosh Mhatre developed an algorithm to control multiple nozzles mounted on the same print head for concurrent printing [65].

2.2.4 Multiple extrusion heads/modular and cooperative manufacturing

The manufacture of parts through multiple and collaborative extrusion modules rises as a potential solution to overcome the limitations of speed, cost, and scalability of common extrusion systems [80, 81]. The research team of Leite et al. termed the interdependencies between time, size and quality as the "3D printing of large parts trilemma" [73]. In collaborative 3D printing, individual mobile 3D printers or extrusion modules collaborate on building a part simultaneously [82]. Leite et al. [73] proposed the use of multiple collaborative deposition heads, and an experimental apparatus [74] was developed as a proof of concept. L. Poudel et al. devised an approach in which multiple print head-carrying mobile robots work cooperatively to print a desired part, which needs to be split into smaller sections that are then allocated to each robot [75]. This study also exposes the need and difficulties in generating efficient, collision free, printing paths, and suggests an innovative generative approach to tackle it. Wachsmuth [72] addresses various issues and concerns that arise while designing a multiple independent extrusion head systems and formulates suitable deposition strategies to reduce build time. Frutuoso [76] developed a slicing software to optimize part positioning and partitioning and proposing how to generate collision avoiding strategies. With the introduction of multiple extrusion heads, new bonding strategies are also needed to join the portions of the part that were produced by the different extrusion heads [72, 83], since the existence of independent extrusion modules imposes the existence of intersections areas in parts. Sardinha et al. [83] threated these intersections as seams, stating that the seams act in a part by creating a localized fragility, diminishing its tensile properties.

The work by Badarinath and Prabhu [77] proposes a modular solution based on retrofitting multiple robotic platforms to incorporate FFF extrusion heads. The authors approach includes a bed compensation algorithm based on bilinear interpolation and real-time synchronization of extrusion position, path, and velocity, with results having a less than 5% error regarding the extrusion widths and heights of manufactured samples. M. Layher et al. proposed a conceptual high-productive system composed of three extruders that use arbitrarily chosen plastics, also addressing model discretization into partial volumes using a specialized developed tool [67]. Similarly, S. Hongyao et al. proposed a large-format cooperative system composed of multiple robots, drafting considerations regarding the influence of the multi-robot layout on the maximum reachable area and geometry adaptability [78]. This work also proposes an optimized scheduling algorithm based on efficiency egalitarianism, and a robot interference avoidance strategy by dividing the printing layer into several safe areas and interference areas, with results showing that the print speed efficiency improvements with four robots exceeds 73% when compared with a general single extrusion method. Underlining the potential in multi extrusion, Zhang et al. developed a data-driven predictive model for the tensile strength of components fabricated by cooperative 3D printing [82]. In a complement to most common literature proposed solutions, the ORNL Manufacturing Demonstration Facility has created a system that works together with an existing BAAM system to 'pick and place' custom components into a part as it is printed [79]. Also mention worthy, Ni. Hopkins unconventional solution suggests that large-format material extrusion problems can be significantly reduced by using hollow tubes in place of solid extrusions, leading to a reduction in material usage and cooling related issues [59]. J. Shah et al. exposed some design consideration and challenges for large-format 3D printers, with a review regarding systems configurations and machine concepts [84]. Similarly, a review by A. Kampker et al. [23] describes machine design trends and highlights the strengths and weaknesses of existing designs.

Figure 1 displays some examples of systems configurations characteristics of LFAM printers.

2.3 Process control

When producing large parts, special attention should be given to the design and preparation stages since a production fail will tend to have impactful losses regarding resources consumption such as time, material, and energy, to name a few [85, 86], and as a result, research has been focused on defect identification and mitigation.

2.3.1 Thermal

With respect to thermal issues, most of the design constraints of small-scale polymer extrusion still apply to LFAM, and additionally, new limitations exist, because large-format systems significantly change the thermal properties associated with small-scale AM, and therefore, temperature profiles throughout large printed structures play an important role in determining its properties and manufacturing success rate [80, 87, 88]. The review of M. Pourali et al. on the thermal modeling of material extrusion AM provides a summary of approaches that have been applied mostly to small-scale polymer extrusion, which should be taken into consideration in BAAM [87].

Inter-layer welding is of special concern, as the large thermal gradients induce residual stresses that can overcome weak inter-layer welds, causing warping and cracking [60, 89]. Aiming at mitigating inter-layer inconsistency, R. Kurfess [89] developed a thermally driven design methodology focused on the interface temperature between layers, establishing a relationship between this temperature, flow rate and print velocity. To better understand the thermal expansion in large area extrusion parts, D. Hoskins et al. [90] compared the coefficient of thermal expansion of a finite element analysis that uses variations along the cross-section of a bead using thermomechanical analysis as input with strain maps using digital image correlation (DIC). K. Choo et al. [85] developed a model that aims at minimizing the risk of failure and slumping of overhanging features by predicting thermally driven fragilities and giving guidance in the decision process during the slicing of parts. Through this model, additional dwell times after each layer are introduced so that the next layer of printing initiates after the previous one is sufficiently cooled and, therefore, the structure is appropriately solidified. B. Friedrich [91] developed a transient thermal simulation model to aid in predicting failure behavior in BAAM, with results allowing to predict and adjust the model to avoid failure during the build process, with

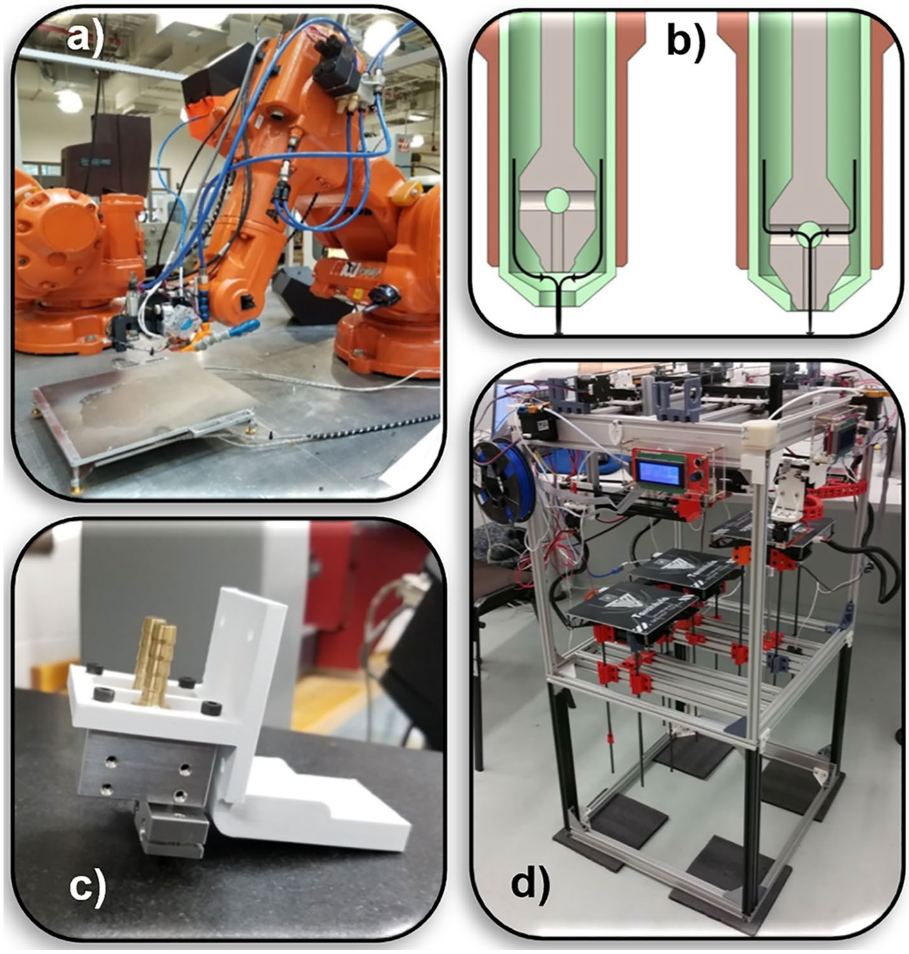

Fig. 1 Systems configurations characteristics of LFAM printers: **a** Robotic arm with a heated printing bead (Adapted from [77] with permission from Elsevier), **b** Pellet extrusion system with variable printing resolution (Adapted from [66] with permission from Elsevier), **c** Dual nozzle extruder (Adapted from [65]) and **d** modular printing system with 3 printing heads (Adapted from [74])

a 5% error achieved in analyzed used cases. Furthermore, researchers at ORNL investigated an in-situ control system comprised of a thermal camera and laser profilometer, which allows to control and adjust material flow and build speed to mitigate defects and uneven build surfaces [86]. F. Wang et al. [63] provided a framework to improve both quality and efficiency of LFAM by employing real-time data captured from an infrared thermal camera and, using a regression model to describe the surface temperature with high accuracy and then control the layer time, promoting high printing efficiency and quality.

2.3.2 Design for AM and modeling approaches

To deal with common problems associated with large polymer extrusion such as temperature related issues described above, design methodologies that anticipate the manufacturing process workflow have proven to be highly efficient at improving manufacturing success rate [92]. A. Roschli et al. detailed significant physical and software-related design considerations for BAAM [80]. In a complementary research [93]**,** the author suggests an overview of how slicing works, how to design for the slicing process, and how to configure slicing for the ideal output. M. Lee's [94] case study of an excavator cabin is an example of how design for BAAM methodologies can improve the feasibility of large polymer parts. In another example, using a cantilever chair as case study, D. Albertini [88] extensively reviews and evaluates the influence of multiple variables on the mechanical behavior of large-format polymer parts, drafts challenges involved with this manufacturing field and derives an equation that aids to define the volumetric flow rate considering both tooling equipment and printing parameters. In line with these results, comparing two different methods, E. Fernández et al. [95] incorporated nozzle size and related constraints into topology optimization to generate suitable designs for large part resolution optimization. Dreifus et al. [96] discussed geometric restrictions of large-format polymer extrusion manufacturing, and by collecting data sets for qualitative analysis of BAAM, provides tools for designers and software developers to improve deposition strategies.

2.3.3 In-process control

Increasingly complex systems impose a need of increasingly accurate control mechanisms. A current natural path in BAAM systems development is therefore to address manufacturing deviations by process control enhancements [55, 66, 70, 97]. Chesser et al. [66] proposed feed-forward extruder control in BAAM to mitigate geometric inaccuracies and low-resolution problems. Silberglied [97] devised a bead characterization system that measures, and with feed forward control predicts and adapts the flow rate of a nozzle. Using finite element thermal modelling, D'Amico and A. Peterson [98] conclude that in BAAM, the temperature and thermal history of extruded beads has important implications for process monitoring, property prediction, and part performance. Using a closed loop control based in a framework for real-time data extraction from thermal images and a novel method for controlling layer time during the printing process, the research by Fathizadan et al. [99] was able to significantly reduce the overall printing time while preserving print quality. Borish et al. investigated the use of a laser profilometer and thermal camera to collect part data as it was being constructed, with results showing significant geometrical improvements [100]. Researchers at ORNL also investigated the use of a thermal camera mounted to a gantry to collect data on an object under construction, for feedback for an in-situ control system to adjust layer build times [101]. The research by Macdonald et al. [102] uses spatial frequency analysis during fabrication and uses this spectral information to infer on surface roughness, delamination, and deposition consistency, while the work by Roschli [70] controls the heat in a limited area in the proximities of the extrusion, allowing to produce consistent beads at variable speeds.

A research effort for improving interlaminar strength and process control of BAAM parts by Duty et al. [60] relates the structure of BAAM materials to the material composition, deposition parameters and resulting mechanical performance. Eyercioglu et al. [103] evaluated thin wall parts by investigating the cooling of single bead layers, and the interface and adjacent top layer temperatures. Kishore et al. studied the potential of using infrared heating for increasing the surface temperature of the printed layer just prior to deposition of new material, to improve the inter-layer strength of components [104, 105]. These studies found significant improvements in bond strength when the surface temperature of the substrate material was increased close to the glass transition temperature, using infrared heating.

In LSPED, due to the large size nature of the print beads, conventional test standards are usually inadequate. Schnittker [106] studied the feasibility of using DIC technology as a key enabler for robust data collection of strain measurements of large 3D printed parts. In complementary research, Schnittker states that DIC data correlated well with failure analysis performed on test coupons [107]. Using DIC, attempts have also been made to build a database of structural performance of large polymer AM parts [108].

2.4 Materials for LFAM

For a material to be successfully utilized for LFAM, a series of fundamental conditions must be met. Duty et al. presented a practical model for evaluating polymer feedstock materials as candidates for LFAM across a variety of extrusion-based platforms [109]. With the absent of a heating chamber and associated problems of part warping during the cooling process due to anisotropic shrinkage, severe delamination, cross-sectional tapering, warpage and sagging can occur [57–59, 110]. Most reported studies concerning LFAM materials focus on thermoplastics, with an emphasis on reinforced thermoplastics [60–63].

2.4.1 2.4.1. Fiber reinforced materials

The work by Kunc et al. [111] investigates the use of PEEK and its composites as potential feedstock for BAAM systems. Thermal and rheological properties were investigated and characterized to identify suitable processing conditions and material flow behavior. Using thermophysical and thermomechanical characterization techniques for fiber-filled ABS, literature reports suggest that Carbon Fiber (CF) reinforced ABS (ABS/CF) has the highest thermal stability to retain the shape at elevated temperature followed by Glass Fiber (GF) reinforced ABS (ABS/GF) and neat ABS [112]. Some studies have performed a rheological characterization of PEI, PPSU, PEKK, PPS, and ABS as well as their composites containing reinforcing fibers [113–116].

A study by Ajinjeru et al. [117] characterized the dynamic rheological behavior of PEI and PEI/CF as BAAM feedstock material. The addition of CF to PEI enhances the shear thinning effect and significantly increasing viscosity, and the needed torque on the extruder. Fiber filled materials are used to counter-act the effects of thermal expansion, but the fibers stay in-plane meaning that no fibers span from layer to layer.

Roschli et al. [110] proposed a "z-pinning" approach, that is based in strategically positioning voids across multiple layers to be latter filled all at once. Duty et al. [118] suggested the same "z-pinning" technique for the reduction of anisotropy in AM polymer parts and improve their interlaminar strength, another possibility is to use a pos-tensioning structure [119].

Development of reinforced thermoplastic compounds that are specifically tailored to BAAM and possess the necessary properties for engineering structures is currently underway [54]. Sánchez et al. [120] developed and characterized CF filled Acrylonitrile Styrene Acrylate (ASA), with rheological, thermal, and mechanical properties of neat ASA and ASA containing 20 wt% CF to address LFAM. Regarding the parametrization of large-format AM techniques, using bio composites and multi-objective optimization, the work of Vijay et al. [57] demonstrated the ability to produce filaments of different shrinkage and tensile strength properties by solely changing process parameters and settings.

2.4.2 Reactive polymers

An alternative approach to fibre reinforced thermoplastics is the utilization of thermoset materials using an extrusion head that combines resin and the hardener during the deposition [45, 46, 121]. Large-format AM of reactive polymer systems offers significant improvements over thermoplastics such as potentially enhanced mechanical properties, faster deposition rates, and deposition at ambient temperatures. Kunc et al. suggested that the use of reactive polymers could reduce the thermally driven deformations and progressive buildup of residual stresses [122]. Unlike thermoplastics, reactive polymers cure during printing through a chemically or thermally initiated reaction and could potentially increase deposition toolpath flexibility and reduce the anisotropy of the printed components by reducing the dependence on temperature control of the process [45, 123], and yield printed parts with inter-layer covalent bonds that significantly improve the strength of the part along the build direction [46]. Lindahl et al. exemplified an AM system capable of depositing reactive polymers in a large format [45]. The work by Hershey et al. implements a design solution for bridging sparse infill patterns in additively manufactured parts while studying the thermal characterization of polymer composites and reactive polymers [124].

2.4.3 Multi-material and/or functionally graded materials

Integrating multiple materials into LFAM is a key for various industrial applications wishing to incorporate site-specific properties into geometrically complex designs, difficult to manufacture with traditional techniques. Brackett et al. [125] used a BAAM system to explore material transitions with a novel dual-hopper that enables in-situ material blending of a pelletized feedstock. The study characterizes a step-change transition between neat ABS and ABS/CF. Furthermore, the application of functionally graded materials and graded material properties transition could significantly advance the applicability of LFAM parts [126].

A list of commercial materials available for LFAM, including the most significant material properties reported by the manufacturers can be found on Annex II.

3 Large-format polymer extrusion deposition—applications

Among the many applications of AM technologies are classical industrial sectors such as aerospace, automotive, architecture, construction, and tooling or small batch manufacturing sectors, with highly diversified and customizable components such as consumer goods, electronics, and healthcare. The 2021 Wohlers Report identifies the market share of AM in different activity sectors, as displayed in Table 3 [4].

It is possible to observe that a significant market portion (almost 50%), is shared by Industrial applications in the Transportation (Automotive and Aerospace), Construction and Energy sectors, where LFAM can play an important role.

In the next sections, examples of applications are shown for the transportation section, industrial applications, energy, and construction. Examples show the potential for application and some short comings associated with LFAM systems.

3.1 Aerospace

Recently, the potential economic gains from mass reduction, are establishing AM as an important fabrication technology in the aerospace industry. In recent years, the aerospace industry has been one of the top sectors leading the AM market (Table 3) and in 2021, 15.9% of the revenue in AM industries was related with the manufacturing of components for aerospace [4]. There are excellent reviews in the works of Najmon et al. [12] and Blakey-Milner et al. [13]. Najmon et al. emphasis is review in technologies and applications in the aerospace. Blakey-Milner et al. review is more focused in metal AM.

The aerospace sector possesses established manufacturing requirements (design complexity, lightweight components,

Table 3 AM market share by industry in 2020. Adapted from [4]

Industry	Market share (%)
Aerospace	16
Automotive	16
Academic institutions	14
Medicine	14
Consumer products and electronics	13
Energy	11
Army	7
Construction	6
Others	3

and flame-retardant materials) that can be successfully fulfilled with the introduction of LFAM technologies. This industry is continuing to benefit from LFAM latest developments regarding; manufacturing of parts with complex designs, fabrication of components that require extensive machining, reducing parts weight, reducing complex assembly efforts, and speeding the time to market of new innovative products. The applications of LFAM in the aerospace sector include aircraft interior and cabin parts; aerodynamic models and mockups; surrogates; prototypes; molds and tooling; unmanned aerial vehicles (UAVs) and rockets.

3.1.1 Aircraft interior and cabin parts

LFAM parts in aircraft interior and cabin parts are essentially applied in non-structural elements. China Eastern airlines explored the use of LFAM to produce spare newspaper holders, electronic flight bag supports [127], and door handle covers [12, 128]. These parts were produced with ULTEM™ 9085 resin, a high-performance thermoplastic material (PEI) with high strength-to-weight ratio compliant to relevant Federal Aviation Administration (FAA) and Civil Aviation Authority of China (CAAC) requirements. China Eastern airlines reports that lead times were reduced from months to days and costs reduced by more than 50%, using LFAM technologies. Lufthansa Technik redesigned and 3D printed a damaged air grill for a 747 Cockpit ventilation duct [129]. This new air grill is a certified part that benefits from better durability, reduced lead times, manufacturing, and maintenance costs. Spacer panels (which fills an end-gap in a row of overhead storage compartments) have been produced by a partnership between Airbus and Materialize for installation on board on the Finnair's A320 aircraft [129]. The panels were produced with flame-retardant Airbus-approved materials and the panels shape has been optimized with a bionic design, to achieve a 15% weight reduction when compared to the original. In 2019, Diel Aviation announced the delivery of its largest fully 3D printed part, a Curtain Comfort Header**,** which was installed on a A350 XWB aircraft [130]. The Curtain Comfort Header is a complex enclosure for the curtain rail, that can have a length of up to 1150 mm. The curtains separate the classes from one another within the cabin. With the 3D printed Curtain Comfort Header, Diel Aviation states that achieved a reduction of tooling parts (complex aluminum tooling for composites were employed) and the advantages of the integration of cable channels, emergency escape route signage and specialized retaining clips on the 3D printed Curtain Comfort Header. Etihad Airways employed LFAM methods to implement a first proof of concept of a full-scale print of an Airbus A320 sidewall with print conductive tracks, antennas, and ornamental features [131]. In a partnership with BigRep company, the sidewalls were printed using 6-axis industrial robots with dual extrusion heads allowing to deposit conductive or capacitive materials.

3.1.2 Aerodynamic models and Mockups

Aerodynamic models are extremely useful to define mathematical models that can describe the aerodynamic forces and moments acting on the airframe of an aircraft during the flight. These models are tested in wind tunnels and are traditionally produced with computer numeric control (CNC) machined metal parts. 3D printed aerodynamic models are typically produced by stereolithography due to its excellent surface finish but are limited in size. The use of aerodynamic models produced by LFAM methods can be found for the development of an M-346 aircraft model [132] and for the F-35 prototyping of fuselage and wing skins by Lockheed Martin [133]. For the M-346 aircraft the test model was printed with PLA on a MakerBot Replicator Z18 3D printer. To obtain a good surface finish, after the printing process the model was polished with sandpaper to smooth the surface and painted applying an acrylic primer and topcoat [132]. Lockheed Martin reports costs savings of $65 K and time savings from 4 weeks to 5 days, by using LFAM methods when compared with conventional CNC machining. Lockheed Martin also saves time by using the LFAM printers to rapidly produce parts such as mockups for the cockpit floor of the F-22 aircraft, with cost savings of $86 K [133].

3.1.3 Surrogates

Surrogates are functional tools which are placeholders for assemblies, used on production floors and in training rooms. Bell helicopters uses LFAM to construct surrogates to assess a hybrid aircraft's tail-wiring configurations, reporting a significant reduction in time (6-week reduction) and costs, when compared with the original cast aluminum parts [134]. These surrogates were produced to build polycarbonate wiring conduits that are placed on the vertical stabilizers for on-the-ground confirmation of the wiring path.

3.1.4 Prototypes

Several prototypes have been produced with LFAM to test a concept or part functionality in the aerospace sector. The use of LFAM for propulsion elements was first presented on an exploratory work by the National Aeronautics and Space Administration (NASA) in 2015, to produce a nonmetallic gas turbine engine. Polymer based components of the project included acoustic liners (Fig. 2a) and inlet guide vanes (Fig. 2b), produced with ABS, ULTEM and ULTEM/CF [135]. Taylor-Deal Automation is another company using LFAM for prototyping, through the production and modification of specialty fluid and air handling parts. Taylor's

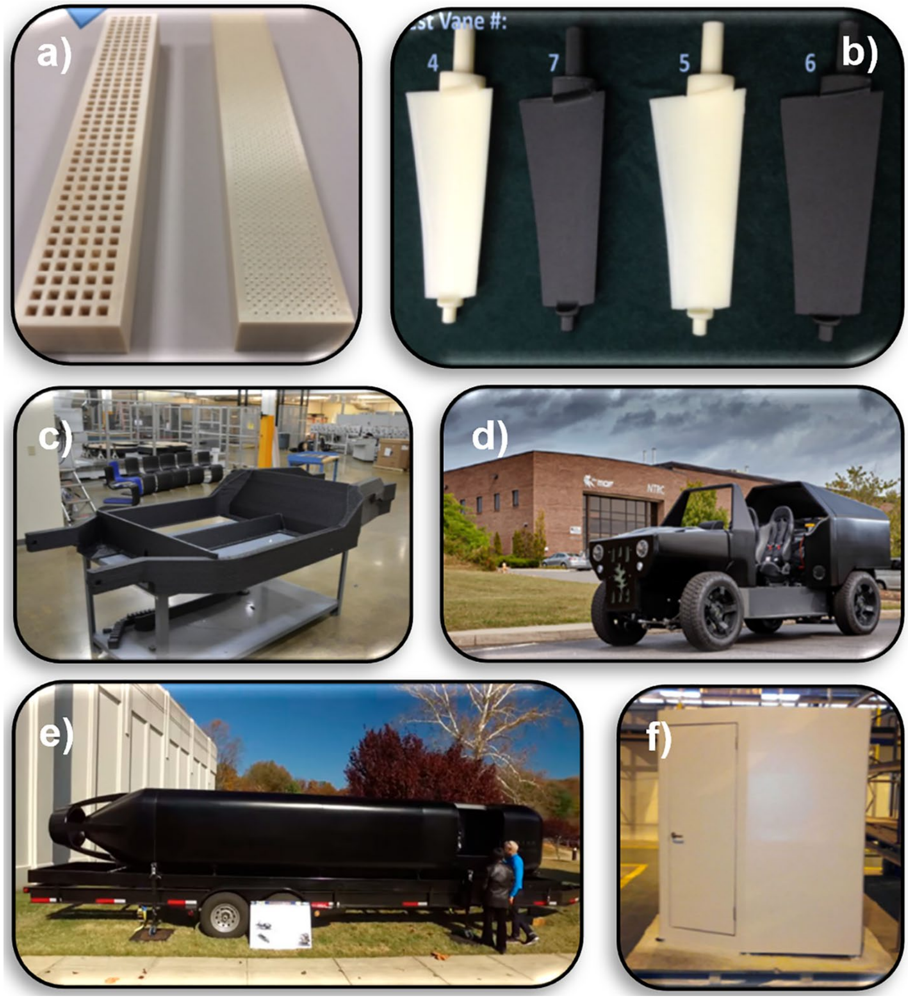

Fig. 2 Applications of LFAM in the transportation sector: **a** Noise attenuation of baseline and advanced acoustic liners and **b** Inlet guide vanes (Adapted from [135]), **c** Printing the chassis of the electric utility vehicle and **d** Completed functional printed utility vehicle (Adapted from [152] with permission from Elsevier), **e** Submarine hull made incremental techniques for the US Navy (Adapted from [158]) and **f** Outside picture of the final WC cabin toilet (Adapted from [56] with permission from Elsevier)

3D printing material of choice is ULTEM® 9085, which meets FAA flame regulations. The 3D printed parts (toroid housings) contain less material, so their weight is approximately one-third of that of the metal parts they replace [134]. Marshall Aerospace and Defense presents a ducting adapter prototype for cooling avionics systems when the aircraft is on the ground. The ducting adapter prototype was made in Nylon 12 and achieved a significant cost reduction compared to machining the part out of aluminum, as well as a 63% reduction in overall weight [136].

3.1.5 Molds and tooling

Advanced Composite Structures produced layup tools for composite materials using AM, reducing costs and production time [134]. Piper Aircraft manufacturer uses LFAM to produce polycarbonate hydroforming tools as an alternative to the traditional CNC aluminum machining, taking advantage of the speed and waste reduction of the LFAM process [134]. Airbus in a collaboration with Autodesk developed a plastic mold for a partition wall with an optimized design. The partition wall was first projected for metal AM but now is defined by a plastic mold which is then cast in a flight-qualified metal alloy [129]. BAE Systems is using LFAM to produce high-temperature mold tooling utilizing a CF reinforced, PEI-based 3D printable resin, in collaboration with Airtech Advanced Materials Group and Ingersoll Machine Tools, Inc. who printed the mold tool on their MasterPrint large-format 3D printing platform. The mold tooling has supported over 250 autoclave cycles, without degradation [137]. CARACOL, an Italian company, has been producing large-format aerospace tools for the positioning and vacuum gripped drilling of airplane fuselage panels for aerostructure with a robotic extrusion system using polypropylene (PP), Polyamide 12 (PA12), polyphenylene sulfide (PPS) with CF and PPS/GF up to 40%. This innovative solution leads to a few benefits for clients such as: halving production times, eliminating the need for manual assembly, cutting material waste, and a significant cost advantage of around 30–50% [138]. Additive Engineering Solutions completed and shipped out a large-format 3D printed 12-foot-long NC vacuum mill holding fixture that will be used by Dassault

Falcon Jet in the trimming and drilling of composite panels [139].

3.1.6 UAVs

The use of AM in UAVs is currently a common practice, due to the less restrictive regulatory procedures that materials and processes are subjected to [134]. Aurora Flight Sciences and Stratasys embarked on an ambitious project: to build a jet-powered remotely piloted aircraft with a wingspan of 2.9 m. The UAV consists of 34 total components, 26 of which were 3D printed and make up about 80% of the aircraft airframe by weight. Using Stratasys Fortus® 3D Printers, the wings and fuselage were produced in ASA thermoplastic, to give the necessary strength and stiffness, but with low density [140].

3.1.7 Rockets

The first application of LFAM technologies in rockets seams to date back to 2014 when the Lockheed & RedEye Team presented two rocket fuel tank prototypes, the bigger one being 2 m long. The tanks were made of a polycarbonate material using a Stratasys Fortus 900 mc FFF machine. Lockheed reports about half the cost, and a lot of save time by 3D printing the tanks in pieces and bonding them together, instead of machining them [141]. In 2016, the United Launch Alliance developed a duct system for the Environmental Control System (ECS) of the Atlas V and Delta IV rockets using LFAM technologies introducing ULTEM 9085 and the Stratasys Fortus 900 mc printer, slashing the system's production cost by 57%, and reducing the ECS assembly from over 140 to 16 production parts [142]. In 2018, the startup Rocket Crafters made the first deployment trial with 3D printed rocket thrusters made of ABS, with a larger custom-made printer and signed a DARPA contract with a $600 K investment. After the hybrid fuel grains are printed, they are further processed by wrapping them in carbon for additional strengthening and then are test fired [143].

3.2 Automotive

The automotive industry is today a major user of AM technologies that fulfil the demanding requirements of such a competitive sector. The competitiveness of automotive industry players is based on their designs capability, and cleaner, lighter, and safer products. Innovative products must reach markets in short lead times with improved fuel efficiency and associated low production costs. The main applications of LFAM in the automotive industry are related with components for cars [144], electric vehicles [145–150], prototypes [151–154], molds and tooling [155–157].

3.2.1 Components for cars

In 2013, Urbee was announced as the first "3D printed car". Urbee is three wheels and two Seats small hybrid car. The 3D printing components of the car include the car body, bumper, and dashboard. These parts were printed with ABS on a LFAM system. The whole car (about 3 m long) takes about 2500 h to be produced [144]. Apart from the fuel drive cars, one segment in which LFAM technologies can be particularly efficient are in Electric Vehicles, due to his capability to provide polymer lightweight components.

3.2.2 Electric vehicles

Local Motors Strati' Car and LM3D Swim are two examples that integrate LFAM technologies to produce parts for electric vehicles. The Strati car was presented in 2014 by a partnership between Local Motors and ORNL, producing a vehicle in days rather than months. This reduction is due to the use of pellets extrusion systems from ORNL and the produced parts include the chassis and skins made with carbon infused ABS [145]. The LM3D Swim was a production version of the Strati Car where roughly 75% of the car is 3D printed, including the body panels and chassis, using the same process and materials employed on the Strati Car [146]. In 2018, the YOYO electric vehicle from XEV received some media attention and is already in production today. The polymer fiber reinforced large parts are produced on a Big Rep PRO printer and for the final surface quality, the 3D printed parts also go through an automated robotic milling process to guarantee a smooth surface. XEV is betting on the customization of the vehicles design surface and body of the car [147]. The Project Chameleon from Scaled Ltd, a firm specialized in large-format 3D printing via a robotic extrusion process, is exploring the LFAM with the use of thermoplastics made from recycled plastics for the chassis of electric vehicles [148] Electric Vehicles truck manufacturers like Nikola Corporation are also exploring LFAM to fabricate fixtures, test models and final parts. Nikola Corporation installed a Big Rep PRO printer for continuous printing with engineering-grade filaments like polyamide 66 (PA66), ABS, ASA or fiber-filled thermoplastics [149]. BCN3D and Elisava Racing Team are introducing LFAM technologies in the electric DAYNA motorbike for producing fenders and fork covers. The Elisava team used BCN3D's largest 3D printer (Epsilon W50) to fabricate the parts with high-temperature CF reinforced polyamide and PP/GF composite filaments [150].

3.2.3 Prototypes

ORNL developed parts prototypes for a Shelby Cobra car [151] and an electric utility vehicle [152] using the ORNL facilities and its polymer extrusion systems with ABS/CF. The prototyped parts include the chassis (Fig. 2c), supports and skins. For both vehicles the frame took approximately 12 h, the skins 8 h, and the supports 4 h to print. The chassis design incorporated threaded rods that could pass through the layers serving two purposes: providing attachment points for drivetrain components and putting the printed material under compression, thus improving the integrity of the chassis. Figure. 2d displays the completed electric vehicle prototype. Ford company is exploring the use of the LFAM to produce room-sized prototypes at Ford's research and innovation center with a Stratasys Infinite Build 3D printer. The printer uses an innovative printing set-up to print parts laterally instead of layer by layer, allowing to print large parts, theoretically with an infinite length. The printer uses a robotic arm to feed the cannisters with thermoplastic pellets and Ford is considering its use to print small-volume parts like spoilers, wings for race cars, molds, jigs and other production aids used in factories [153]. Also, in the prototype phase are non-Pneumatic (airless) tires from various manufacturers. In the recent work of Jafferson et Sharma [154], a review of the innovations in airless tires and the unique designs that are used are presented. The authors present a study considering a set of lattice structures potentially produced on the Big Rep—Thermoplastic Polyurethane (TPU) material fabrication platform.

3.2.4 Molds and tooling

Molds and tooling for the automotive industry are traditionally made with non-AM methods, but in the last decade, this paradigm has changed and today we can already find some examples of the use of LFAM technologies for molds and tools in this industry. Polimotor was the first company to develop an automotive engine with several polymer parts and today is working with Ford on a prototype composite engine. Polimotor in a partnership with ORNL studied the application of LFAM technologies in the production of an injection mold for an oil pan for use in a composite engine [155]. The mold was produced using a hybrid approach: the large bulk of the mold was printed with the ORNL BAAM system with carbon fiber-filled ABS and the detailed molding surfaces were printed on a Stratasys Fortus 900 out of ULTEM 9085. Another company that explores the LFAM technique to produce tools and molds for the automotive industry is DTG, which in cooperation with ORNL studied the production of a check fixture and a sand-casting mold [156]. The check fixture was printed using ABS/CF polymer. Sand-casting molds were produced using the same material, the larger section of the mold had a maximum size of 1.4 m and took 6 h to print. After printing, the casting pattern went through a machining process. On the work of Henderson et al. [157], cope and drag casting aluminium sand-casting molds for the automotive industry were also produced by LFAM technologies using a Stratasys Fortus 900mc system and ULTEM, with a nozzle diameter of 0.25 mm and layer height of 0.125 mm. The authors believe to have demonstrated the compatibility between printed patterns and traditional casting foundry practices and that both lead time and cost are reduced when compared with subtractive technologies.

3.3 Naval

The naval industry, is a traditional sector where significant processes and practices are based on experience, making this sector a late adopter of AM techniques [158]. However, recent advances regarding reliability, material developments and printing sizes of AM, have permitted the introduction of some of these technologies in the naval industry, with the applications identified on this work being partition wall panels, a submarine hull, autonomous underwater vehicles, and molds.

In 2017, the U.S. Navy, in collaboration with ORNL produced a composite submarine hull (Fig. 2e) made of ABS/CF in a LFAM system. The built hull is a sea, air, and land (SEAL) delivery vehicle. The use of LFAM methods allowed to reduce the production time and achieve a cost reduction up to 90% [158].

A case study reporting the fabrication of partition wall panels for cabin toilets for installation on tankers or bulk carriers was presented by Nieto et al. [56]. On this work, the authors utilized the S-Discovery printer (a pellet-based machine) to print wall panels up to 1.3 m, reducing the cabin's original weight by 64.4% with PLA and by 55.5% when using flame-retardant ABS. Figure. 2f displays the assembly of the final prototype.

Dive Technologies is producing geometrically complex fairings for autonomous underwater vehicles, using a LFAM systems from Cincinnati Inc, in less than 48 h for an entire vehicle [159].

One potential application of LFAM techniques in the naval industry are boat molds. ORNL studies the feasibility of use LFAM to directly manufacture vacuum assisted resin transfer molding (VARTM) boat molds in collaboration with Alliance MG [160]. The proposed boat mold tested is approximately 11 m long and was produced in sections of 1.8 m, using the BAAM system of ORNL, with ABS/CF and a 7.5 mm nozzle and a 3.75 mm layer height. After printing, the molds were machined, polished with sandpapers, and coated with a vinyl ester mold surface agent.

Figure 2 displays some applications of LFAM in the transportation sector.

3.4 Academic applications

Academic institutions are traditionally a forum for the dissemination and teaching of innovative technologies such as AM technologies. Regarding AM using LFAM methods, we can already find some examples of its use in the academic context, namely in the development of prototypes [161, 162] and sustainable use of materials [163, 164].

In 2016, the ORNL launched the "3D-Printed Excavator Project" in cooperation with the industry and the University of Illinois. The main objective of the project was to develop heavy construction machinery. In this context, a 3D-Printed cabin prototype produced with ABS reinforced with carbon fiber ABS/CF prototype was produced to evaluate the design of the excavator cabin [161].

Another example of a prototype produced with LFAM methods in a context of an academic work was the printing of a model of an embankment dam, a partnership was established between M. Leite team and the Hydraulics Laboratory of Instituto Superior Técnico, under the scope of the project Big FDM [162]. The model with a volume of $1500 \times 395 \times 310$ mm was obtained by acquiring a point cloud from a smaller scale experimental model, resulting in a mesh surface. The modular 3D Printer of the Big FDM project was configured to use three independent print platforms, and on each one, two deposition modules collaboratively fabricated the part. This case study allowed significant developments in terms of trajectory planning, collaborative manufacturing, and validation in a productive environment. The model was then used in fluid dynamics experimental tests in the hydraulics laboratory.

A partnership between ORNL and the University of Maine studied the application of bioderived materials for application in large-format AM [163, 164]. The objective of the program was to conduct fundamental research in areas such as: cellulose nanofiber production, compounding with thermoplastics and sustainability life-cycle analysis. The demonstration of the technology was performed by the 3D printing of a part (podium base), using PLA reinforced with poplar fibers, after the material properties have been estimated [164].

3.5 Construction sector

One of the first applications of AM in architecture and construction sectors was the production of mockups.

Small-scale models give architects freedom to test their ideas, rethink the designs and explore new functionalities [165]. The use of AM in construction started with the cementitious materials and was assisted by the development of the techniques of contour crafting and 3D concrete printing [166]. Although the use of AM cementitious materials is the most common, polymer materials could have an aesthetic or structural role to play in these sectors. Camacho et al. presented a review of applications of AM in the construction industry [9]. The main applications of LFAM in architecture and construction include architectural models, houses, windows, furniture and decorative items and molds for off-site construction.

3.5.1 Architectural models

Suntem 3D created a 3D printed architectural model of the Turning Torso building by architect Santiago Calatrava, using BCN3D Sigma machines. After 137 h of 3D printing, a physical PLA model of the building was ready. The mock-up was made in a scale of 1/135 and measured 1.40 m [167]. Big Rep is applying LFAM to implement architectural models using PLA on the Big Rep STUDIO printer for a Villa design. The total printing time for the 12 sections of the Villa design model is 120 h. To obtain a smooth painted finish, manually post-processing is done by sanding and painting the external surfaces. The full architectural model took 11 days to produce, a 50% reduction in both production time and labor costs [168].

3.5.2 3.5.2 Houses

In 2014, the project "3D Print Canal House" developed by the designing company Dus Architects used a biodegradable thermoplastic to demonstrate the construction of a building. Printed with a large 3D printed called Kamer Maker, the house components were directly produced on site, minimizing building waste and transport costs [169]. The Additive Manufacturing Integrated Energy (AMIE) demonstration project includes the fabrication of a house with LFAM, Fig. 3a. Approximately 80% of the house, including the segments, were 3D printed with ABS/CF using ORNL system with a deposition rate of 45 kg/h. The house has an area of 19.5 m^2 and was built to serve as an example of the capabilities of AM in the construction industry, producing an energy efficient building with less material waste [9, 170]. The Chinese company Qingdao Unique Products Development Co Ltd developed a large size 3D printer ($12 \times 12 \times 12$ m) to print an entire house with GF reinforced graphene [171].

3.5.3 Window frames

One disruptive application of LFAM in the construction sector may be to produce window frames. A techno-economic viability study performed by Love et al. [172], showed that LFAM technologies can enhance the customization level of window frames, with cost and energy savings, when compared with the traditional fabrication methods. The structural

Fig. 3 Applications of LFAM in the architecture and construction sector: **a** AMIE building in USA (Adapted from [152] with permission from Elsevier), **b** Chair made using PLA mixed with black colorant (Adapted from [173] with permission from Elsevier) and **c** Bevis marks roof cladding (Adapted from [9] with permission from Elsevier)

testing proved to be viable in both material strength and energy efficacy.

3.5.4 Furniture and decorative items

Furniture and decorative items employing LFAM include chairs, tables, or decorative claddings. Chairs have been produced in PLA in cartesian 3D printers [88] or a robotic arm [173], Fig. 3b. A sample table with dimensions of almost 1 m was printed on the BAAM machine developed by the ORNL in 1 h and 43 min [69]. A construction company that has explored the benefits of LFAM is Skanska, through the production of unique cladding for the Bevis Marks Building in London, Fig. 3c. Polymer parts produced for the Bevis Marks Building had decorative purposes only, even so, they test the safety and reliability of AM components, and their use in large-format structural applications [9].

3.5.5 Molds for off-site construction

ORNL worked with Gate Precast to demonstrate the viability of using ABS/CF and BAAM technology by manufacturing molds for the precast concrete industry. The authors state that using BAAM, they are able to demonstrate a significant reduction in costs and that future research will attempt to employ materials, such as ABS/GF or PLA reinforced with wood flour, to bring the cost down even further [174].

Figure 3 displays some applications of LFAM in the architecture and construction sector.

3.6 Energy sector

AM has the potential to revolutionize many aspects of the energy sector, accelerating and changing the way companies implement new technologies. AM can support and supplement the existing infrastructures that surround sector activities, and early adoption of AM could increase market-competitiveness and give unforeseen advantages to new industry players, especially given the increasing demand for reductions in costs and delivery time. Some of the key benefits of AM that will drive its faster adoption within the energy sector can be linked with: higher design flexibility and simplification of components; scaled asset testing and evaluation; improved supply chain sustainability; reproduction and repair of complex or obsolete equipment parts; possibility of tailor material properties and geometries [175]. The notable applications of LFAM in the energy sector include wind turbines, hydropower components, magnets, and molds.

3.6.1 Wind turbines

One of the main applications of LFAM in the energy sector is wind turbines, that can be whether for the development of prototypes, wind turbine blades, diverters or nacelle covers.

In 2014, Abdelrahman and Johnson [176] tested the application of LFAM to produce a prototype for a wind turbine test rig with a modular blade (based on the S833 airfoil design) using 3D printed PC-ABS material. The blade measure 1.7 m with a section width of approximately 0.2 m, Fig. 4a. The authors state that the implemented experimental set-up with 3D printed blades sections was effective in measuring small changes in strain within the wind turbine blade. Beyond the prototyping phase, LFAM methods have been applied in applications of horizontal and vertical wind turbine blades. In 2018, the ORNL in collaboration with XZERES Wind fabricated a small (in comparison to traditional wind energy systems) horizontal wind turbine blade using LFAM methods [177]. The prototype blades with 0.9 m were produced with a 2.5 mm nozzle using ABS/CF on the ORNL BAAM system and mechanical tests showed that the failure of blades occurred high above (3.4 times) the maximum ultimate load determined in the standards. Vertical wind turbine diverters were also produced using LFAM

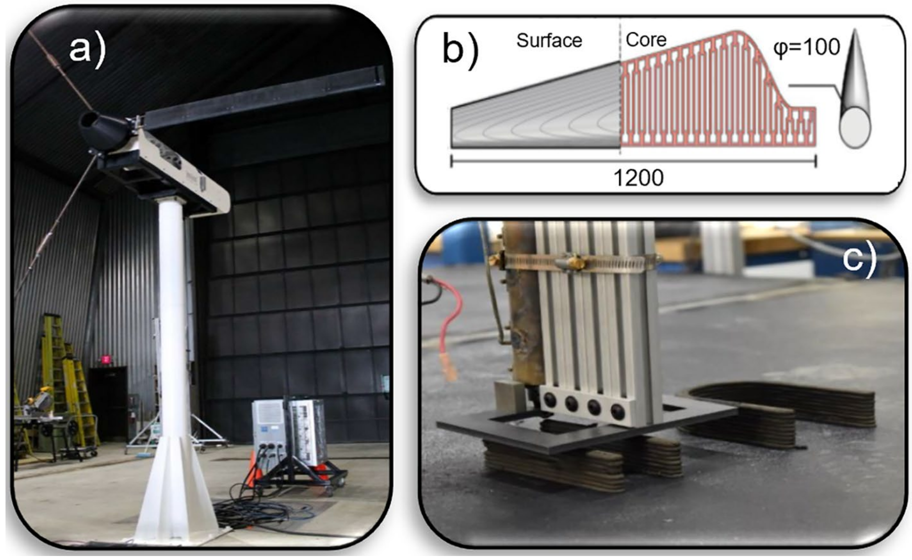

Fig. 4 Applications of LFAM in the energy sector: **a** 3D printed vertical wind turbine blade (Adapted from [176]), **b** Design surface and ore structure of a wind turbine blade with cellulosic materials (Adapted from [180]) and **c** Two Nd-Fe-B sintered magnets (Adapted from [185] with permission from Elsevier). All dimensions are in millimeters

technologies. ORNL worked with Hover Energy LLC on the design of LFAM components [178]. A design modification to fabricate vertical wind turbine diverters using LFAM was performed, and the diverters were analyzed based on anticipated wind loading. The 1/3 scale diverters models with 1.2 m in length were printed with a 2.5 mm nozzle on the ORNL BAAM system. The authors expect reductions in costs and lead times, when compared with the previously employed hand-layup method to produce the vertical wind turbine diverters. The use of AM to produce wind turbines allow to fabricate these parts with internal structures or variable infill patterns which facilitates the design for functionality of these components, as well as reducing their weight. In 2018, a mid-span blade of a wind turbine blade from XZERES Corp (442SR) with a length of 2.8 m was printed with a variable infill pattern, adapted to the estimated deflection loads by finite element analysis (FEA) that the blade faces during service [179]. The applied infill pattern has a functionally graded honeycomb with higher density of hexagons where high stresses are estimated. The mid-span blades were printed using ABS/CF and TPUs with a foaming agent at the ORNL BAAM system. The authors also implemented a new slicing method for the graded honeycomb infill pattern. The obtained results represent a potential reduction in fabrication time and weight of wind turbine blades produced by LFAM methods. Another example of wind turbine blades with internal structures is the work of Sanandiya et al. [180]. In this work, a wind turbine (1.2 m) with an internal structure (Fig. 4b) was printed using a robotic arm, with cellulosic materials. The cellulosic material has a density less than one half that of the lightest commercially available 3D printed filament (Polyamide, 0.95 g/cm3), resulting in a lightweight finished blade of 5.28 kg. Nacelles covers are components of wind turbines that can provide aerodynamic shell around the wind turbine components and a safety barrier. A nacelle cover was produced by ORNL on the AMIE structure [181], and details from this construction were already described on this paper (Sect. 2.3.2).

3.6.2 Hydropower components

LFAM technologies are being studied as a potential process to produce parts for low-head hydropower systems. ORNL worked with AMJET Turbine Systems to demonstrate LFAM of components for low-head hydro turbine/generator parts, namely: stator vane body, stator outer, bell plug and draft tube [182]. ORNL tested several LFAM systems that include the Stratasys Fortus 900mc printer, the Cosine AM1 printer and the BAAM ORNL system. The authors find some limitations of the BAAM to produce parts, since components did not adequately perform due to persistent leaks caused by porosity and suggest the vacuum infusion of resin of parts to solve this problem. Another example of application of LFAM technologies in low-head hydropower results from a partnership between ORNL and Cadens to produce low-cost parts [183]. The fabricated parts on the BAAM ORNL system include a draft tube, a thimble, and a runner housing layup mold. The project provided an opportunity for Cadens to scale up their modular AM hydropower parts using the capabilities of BAAM.

3.6.3 Magnets

LFAM printed magnets are an emerging technology in the energy sector in direct drive wind turbines, since these systems require large permanent magnets. Direct drive wind turbines have some advantages when compared to gearbox wind turbines since the gearbox is the heaviest and the most maintenance costly part of a turbine. LFAM printed magnets were produced by BAAM in the ORNL using NdFeB [184] or NdFeB + SmFeN [185] powders on a Nylon 12 matrix. The prototyped magnets were a cylinder (15 cm length), and horse-shoe shaped magnet (5 cm square), Fig. 4c.

3.6.4 3.6.4 Molds

LFAM technologies are already a reality regarding its application to molds production for the energy industry, namely in wind turbines blades. The main use of LFAM is for the implementation of vacuum assisted resin transfer mold, for wind turbines blades [186, 187]. ORNL demonstrated this by building 13 m long windmill blades. The mold was produced with ABS/CF in multiple 1.8 m sections, that were aligned and joined together. The molds were coated with 8 mm of fiberglass that was machined

Table 4 Applications of LSPED technologies in the different activity sectors

Sectors	Applications	
Aerospace	Aircraft interior and cabin parts China Eastern Airlines Spare newspaper holders and electronic flight bag supports [116] China Eastern Airlines Door handle covers [11, 117] Air grill—Lufthansa Technik [118] Spacer Panel – Airbus [118] Curtain Header – Diehl Aviation [119] Airbus A320 sidewall – Etihad Airways [120] Aerodynamic models and mockups [121, 122] Prototypes Marshall Aerospace and Defence—Ducting adapter [125] NASA – Inlet guide vanes (IGVs) and acoustic liners [124] Taylor-Deal Automation Fluid and air handling parts [123]	Molds and Tooling Advanced Composite Structures – Layup tools [123] Piper Aircraft – Polycarbonate Hydro-forming Tools [123] Airbus – Autodesk – Plastic mold for a partition wall [118] BAE Systems [126] CARACOL [127] Additive Engineering Solutions [128] Rockets Lockheed – Rocket Fuel Tanks [130] 3D Printed Rocket Thrusters [132] United Launch Alliance –ECS duct system [131] Unmanned Aerial Vehicles Aurora Flight Sciences [129] Surrogates Bell Helicopter [123]
Automotive	Components for Cars Urbee Car [133] Electric Vehicles Strati Car [134] LM3D Swim [135] YOYO [136] Project Chameleon Platform [137] Nikola Corporation (EV Trucks) [138]	Motorcycles Fender and Fork Covers [139] Prototypes 3-D-Printed Shelby Cobra [140] ORNL Utility Vehicle [141] Ford – Stratasys [142] Airless tires [143]
Naval	Submarine Hull [147] WC Cabins [44]	Drones- Dive Technologies [148] Molds [149]
Academic applications	Prototypes Excavator Cabin [150] Embankment Dam Model [151]	Bioderived Materials PLA reinforced with Poplar fibers [153]
Architecture and construction	Architectural Models BCN3D – SUNTEM 3D [156] BigRep STUDIO [157] Houses Canal House in Amsterdam (Kamer Maker) [158] AMIE structure (ORNL BAAM system) [159] Qingdao Unique Products [160]	Windows [161] Furniture and Decorative items Skanska cladding [8] Chairs and Tables [59, 78, 162] Off-site Construction Concrete Molds [163]
Energy	Wind Turbines Prototypes [165] Horizontal wind turbine blades [166] Vertical Wind Turbines Diverters [167] Wind Turbines Blades with Internal Structures [168, 169] Nacelle covers [170]	Hydropower Turbine Components [171] Tubes [172] Magnets [173, 174] Molds and Tooling [175, 176]

to the final surface geometry and finish. To achieve a uniform temperature on the surface of the mold, optimized air channels were printed, to allow heating of the tools via forced heated air. These channels create time and cost savings by eliminating the step of making the traditional resistive heating system.

Figure 4 displays some applications of LFAM in the energy sector.

Table 4 summarizes the applications of LFAM technologies in the different activity sectors that were mentioned above.

4 Challenges and opportunities

Of course, there are shared challenges for current AM extrusion systems, such as modelling tools, development of sustainable materials free from oil dependence, specifications, and standards development and intellectual property, for example. However, some are more important in the case of LSPED, such as process control, inspection criteria or strategies for cost-effective printing.

The review of the issues and solutions concerning LFAM and exhibition of application for several sectors balance the future challenges and opportunities for LFAM. Identified challenges affect several steps of AM value chain, from modelling parts to process control or materials selection. This challenges also open research opportunities to academy and industry to innovate. These new necessary systems must take in consideration scalability, higher production rates and must remain within a competitive cost range. Future systems must also take in consideration the possibility of multiple processing (processing and post-processing) or hybrid systems with additive and subtractive manufacturing. Opportunities arise from usage of multiple materials platforms capable of 3D printing parts with functionally graded systems. Material reduction systems such as new infill strategies for further weight reduction are important for non-structural parts, but LFAM must fulfill requirements concerning multifunctional and structural applications.

One aspect of LFAM not referred in this work is the potential impact in MRO operations. In the later years, researchers started to perceive the potential of AM in industrial maintenance, particularly in spare parts manufacturing. By allowing toolless manufacturing, and large design freedom, AM technologies can be used to produce spare parts “on-demand”, thus contributing to improve maintenance efficiency and effectiveness [188–190].

5 Conclusions

AM of polymer large parts is a technological research area with a great growth potential, but significant barriers to its implementation need to successfully be addressed. The main advances in these technologies are linked with the possibility of producing large polymer parts in a faster, cheaper, and reliable way. Parts may present higher degree of complexity, multiple combinations of materials and functionalities. These large polymer components should also meet functional requirements (metrology, mechanical performance, and thermal behavior) for structural applications, and be developed accordingly with industry standards.

This work aims to identify current and future needs for the development of AM large polymer parts and its successful implementation.

A state of the art of polymer large parts produced by AM was conducted through a bibliographic and market research aiming to identify available AM systems for large polymer parts, the technical characteristics of these manufacturing systems and adjacent research directions that could allow performance the improvement of AM systems for large polymer parts. The state-of-the-art present in this work permits to draw the following conclusions:

- Current available AM systems for large polymer parts ($> 1\ m^3$) are mostly based on extrusion methods. These AM systems are commonly expensive (up to 400 K), and the ones based on the FFF technology are characterized by relative low deposition rates (< 0.5 kg/h).
- Several solutions have been proposed to overcome the limitations of these systems, namely the use of machines with robotic arms, adaptable nozzle sizes, or multiple and independent extrusion heads.
- Nowadays, the utilization of AM for the fabrication of medium and large polymer parts is already a trend in many activity sectors.

Future developments of polymer large parts with AM will depend on addressing technological gaps trough the definition of innovative modeling and design approaches, materials, manufacturing systems, standards, specifications, and testing methods that ensure the reliability of these developments. Besides the technical resolution of the challenges that AM of large polymeric parts presents, it is also essential to understand the vision of the various AM players (academy, entrepreneurs, and industry, among many others) in relation to AM of large polymeric parts, as well as what are their expectations for the future. The successful consolidation concerning the use of AM for the fabrication of large polymer parts will pave the way for new AM services, manufacturing systems and products that will offer comparative advantages and business opportunities to the early adopters of this technology.

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Data availability Not applicable.

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Declarations

Conflict of interest Luís Reis, António Ribeiro, and Marco Leite, are inventors of the patent with the title: "Modular additive manufacturing system", with the international publication number: WO2018/080331.

References

1. ISO, ASTM (2021) ISO/ASTM 52900:2021 - Additive manufacturing — General principles—Fundamentals and vocabulary. https://doi.org/10.1520/F3177-21
2. Bourell DL, Beaman JJ, Leu MC, Rosen DW (2009) A Brief history of additive manufacturing and the 2009 roadmap for additive manufacturing: looking back and looking ahead. In: US – Turkey workshop on rapid technologies
3. Beaman JJ, Bourell DL, Seepersad CC, Kovar D (2020) Additive manufacturing review: early past to current practice. J Manuf Sci Eng Trans ASME 142:110812–110832. https://doi.org/10.1115/1.4048193/1086507
4. Wohlers T, Campbell RI, Diegel O, et al (2021) Wohlers Report 2021-3D Printing and additive manufacturing-State of the Industry.
5. Karevska S, Steinberg G, Muller A, et al (2019) 3D printing: hype or game changer? A Global EY Report
6. SmarTech (2019) Polymer additive manufacturing markets and applications: 2020–2029
7. Ngo TD, Kashani A, Imbalzano G et al (2018) Additive manufacturing (3D printing): a review of materials, methods, applications and challenges. Compos Part B Eng 143:172–196. https://doi.org/10.1016/j.compositesb.2018.02.012
8. Alghamdi SS, John S, Choudhury NR, Dutta NK (2021) Additive manufacturing of polymer materials: progress, promise and challenges. Polym. https://doi.org/10.3390/POLYM13050753
9. Camacho DD, Clayton P, O'Brien WJ et al (2018) Applications of additive manufacturing in the construction industry – a forward-looking review. Autom Constr 89:110–119. https://doi.org/10.1016/j.autcon.2017.12.031
10. Paolini A, Kollmannsberger S, Rank E (2019) Additive manufacturing in construction: a review on processes, applications, and digital planning methods. Addit Manuf. https://doi.org/10.1016/j.addma.2019.100894
11. Culmone C, Smit G, Breedveld P (2019) Additive manufacturing of medical instruments: a state-of-the-art review. Addit Manuf 27:461–473. https://doi.org/10.1016/J.ADDMA.2019.03.015
12. Najmon JC, Raeisi S, Tovar A (2019) Review of additive manufacturing technologies and applications in the aerospace industry. Addit Manuf Aerosp Ind. https://doi.org/10.1016/B978-0-12-814062-8.00002-9
13. Blakey-Milner B, Gradl P, Snedden G et al (2021) Metal additive manufacturing in aerospace: a review. Mater Des. https://doi.org/10.1016/j.matdes.2021.110008
14. Salifu S, Desai D, Ogunbiyi O, Mwale K (2022) Recent development in the additive manufacturing of polymer-based composites for automotive structures—a review. Int J Adv Manuf Technol 119:6877–6891. https://doi.org/10.1007/s00170-021-08569-z
15. Li N, Huang S, Zhang G et al (2019) Progress in additive manufacturing on new materials: a review. J Mater Sci Technol 35:242–269. https://doi.org/10.1016/j.jmst.2018.09.002
16. Zhang C, Chen F, Huang Z et al (2019) Additive manufacturing of functionally graded materials: a review. Mater Sci Eng A. https://doi.org/10.1016/j.msea.2019.138209
17. Liu S, Shin YC (2019) Additive manufacturing of Ti6Al4V alloy: a review. Mater Des. https://doi.org/10.1016/j.matdes.2018.107552
18. Bajaj P, Hariharan A, Kini A et al (2020) Steels in additive manufacturing: a review of their microstructure and properties. Mater Sci Eng A. https://doi.org/10.1016/j.msea.2019.138633
19. Askari M, Hutchins DA, Thomas PJ et al (2020) Additive manufacturing of metamaterials: a review. Addit Manuf. https://doi.org/10.1016/j.addma.2020.101562
20. Haghdadi N, Laleh M, Moyle M, Primig S (2021) Additive manufacturing of steels: a review of achievements and challenges. J Mater Sci 56:64–107. https://doi.org/10.1007/s10853-020-05109-0
21. Loh GH, Pei E, Harrison D, Monzón MD (2018) An overview of functionally graded additive manufacturing. Addit Manuf 23:34–44. https://doi.org/10.1016/j.addma.2018.06.023
22. Picard M, Mohanty AK, Misra M (2020) Recent advances in additive manufacturing of engineering thermoplastics: challenges and opportunities. RSC Adv 10:36058–36089. https://doi.org/10.1039/D0RA04857G
23. Kampker A, Triebs J, Kawollek S et al (2019) Review on machine designs of material extrusion based additive manufacturing (AM) systems - status-quo and potential analysis for future am systems. Procedia CIRP 81:815–819. https://doi.org/10.1016/j.procir.2019.03.205
24. Urhal P, Weightman A, Diver C, Bartolo P (2019) Robot assisted additive manufacturing: a review. Robot Comput Integr Manuf 59:335–345. https://doi.org/10.1016/j.rcim.2019.05.005
25. Wiberg A, Persson J, Ölvander J (2019) Design for additive manufacturing – a review of available design methods and software. Rapid Prototyp J 25:1080–1094. https://doi.org/10.1108/RPJ-10-2018-0262

26. Plocher J, Panesar A (2019) Review on design and structural optimisation in additive manufacturing: Towards next-generation lightweight structures. Mater Des. https://doi.org/10.1016/j.matdes.2019.108164
27. Plessis A, Broeckhoven C, Yadroitsava I et al (2019) Beautiful and functional: a review of biomimetic design in additive manufacturing. Addit Manuf 27:408–427. https://doi.org/10.1016/j.addma.2019.03.033
28. Zhu J, Zhou H, Wang C et al (2021) A review of topology optimization for additive manufacturing: Status and challenges. Chinese J Aeronaut 34:91–110. https://doi.org/10.1016/j.cja.2020.09.020
29. Lindgren L-E, Lundbäck A (2018) Approaches in computational welding mechanics applied to additive manufacturing: review and outlook. Comptes Rendus Mécanique 346:1033–1042. https://doi.org/10.1016/j.crme.2018.08.004
30. Haleem A, Javaid M (2019) Additive manufacturing applications in industry 40: a review. J Ind Integr Manag. https://doi.org/10.1142/S2424862219300011
31. Savolainen J, Collan M (2020) How additive manufacturing technology changes business models? – review of literature. Addit Manuf. https://doi.org/10.1016/j.addma.2020.101070
32. Post BK, Lind RF, Lloyd PD, et al (2016) The Economics of big area additive manufacturing. in: international solid freeform fabrication symposium. University of Texas at Austin
33. Tiwary VK, P. A, Malik VR, (2021) An overview on joining/welding as post-processing technique to circumvent the build volume limitation of an FDM-3D printer. Rapid Prototyp J 27:808–821. https://doi.org/10.1108/RPJ-10-2020-0265
34. Love LJ, Duty CE, Post BK, et al (2015) Breaking barriers in polymer additive manufacturing. in: sampe 2015- society for the advancement of material and process engineering. Baltimore
35. Holm J, Dumfort A (2020) A review on recent developments in fused deposition modeling and large-scale direct pellet extrusion of polymer composites
36. Moreno Nieto D, Molina SI (2020) Large-format fused deposition additive manufacturing: a review. Rapid Prototyp J 26:793–799. https://doi.org/10.1108/RPJ-05-2018-0126/FULL/PDF
37. Gülcan O, Günaydın K, Tamer A (2021) The state of the art of material jetting-a critical review. Polymers (Basel). https://doi.org/10.3390/POLYM13162829
38. MIMAKI (2022) 3DGD-1800 | Product | MIMAKI. https://mimaki.com/product/3d/3d-gdp/3dgd-1800/. Accessed 25 Jul 2022
39. Goodridge R, Ziegelmeier S (2017) Powder bed fusion of polymers. Laser Addit Manuf Mater Des Technol Appl. https://doi.org/10.1016/B978-0-08-100433-3.00007-5
40. TPM3D (2022) TPM3D S800DL. https://english.tpm3d.com/index.php?m=content&c=index&a=show&catid=17&id=20. Accessed 25 Jul 2022
41. Mostafae A et al (2021) Binder jet 3D printing—process parameters, materials, properties, modeling, and challenges. Prog Mater Sci 119:100707
42. Voxeljet (2022) VX1000 - Multi material 3D printer for small series. https://www.voxeljet.com/industrial-3d-printer/prototyping/vx1000/. Accessed 27 Apr 2022
43. Pagac M, Hajnys J, Ma QP et al (2021) A review of vat photopolymerization technology: materials, applications, challenges, and future trends of 3d printing. Polym. https://doi.org/10.3390/POLYM13040598
44. Materialise (2022) Stereolithography (SLA) | 3D Printing Technology | Materialise. https://www.materialise.com/en/industrial/3d-printing-technologies/stereolithography. Accessed 10 Nov 2022
45. Lindahl J, Hassen AA (2018) Large-scale additive manufacturing with reactive polymers. in: the composites and advanced materials expo. Dallas United States of America
46. Rios O, Carter W, Post B et al (2018) 3D printing via ambient reactive extrusion. Mater Today Commun 15:333–336. https://doi.org/10.1016/j.mtcomm.2018.02.031
47. Masood SH (2014) Advances in fused deposition modeling. In: comprehensive materials processing, 1st ed. Elsevier 69–91
48. ATMAT (2022) Jupiter - Unlimited space of opportunities
49. Thermwood (2020) LSAM2020 Brochure
50. Go J, Schiffres SN, Stevens AG, Hart AJ (2017) Rate limits of additive manufacturing by fused filament fabrication and guidelines for high-throughput system design. Addit Manuf 16:1–11. https://doi.org/10.1016/j.addma.2017.03.007
51. Jiang S (2017) Processing rate and energy consumption analysis for additive manufacturing processes : material extrusion and powder bed fusion. Massachusetts Institute of Technology
52. Gutowski T, Jiang S, al et, (2017) Note on the rate and energy efficiency limits for additive manufacturing. J Ind Ecol 21:S69–S79. https://doi.org/10.1111/jiec.12664
53. Richardson BS, Love LJ, Chesser PC et al (2018). Enabling Technologies for Medium Additive Manufacturing (MAAM). https://doi.org/10.2172/1430617
54. Hill C, Bedsole R, Rowe K, et al (2018) Big area additive manufacturing (BAAM) materials development and reinforcement with advanced composites. https://doi.org/10.2172/1434289
55. Wang Z, Liu R, Sparks T, Liou F (2016) Large-Scale Deposition System by an Industrial Robot (I): design of fused pellet modeling system and extrusion process analysis. 3D Print Addit Manuf https://doi.org/10.1089/3dp.2015.0029
56. Moreno Nieto D, Casal López V, Molina SI (2018) Large-format polymeric pellet-based additive manufacturing for the naval industry. Addit Manuf 23:79–85. https://doi.org/10.1016/j.addma.2018.07.012
57. Vijay Y, Sanandiya ND, Dritsas S, Fernandez JG (2019) Control of process settings for large-scale additive manufacturing with sustainable natural composites. J Mech Des. https://doi.org/10.1115/1.4042624
58. Seokpum K, Harsh B, Arabi HA, et al (2019) Analysis on part distortion and residual stress in big area additive manufacturing with carbon fiber-reinforced thermoplastic using dehomogenization technique. In: The composites and advanced materials expo. California, United States of America
59. Hopkins N, van Vuuren RJ, Brooks H (2020) Additive manufacturing via tube extrusion (AMTEx). Addit Manuf. https://doi.org/10.1016/j.addma.2020.101606
60. Duty CE, Kunc V, Compton B et al (2017) Structure and mechanical behavior of big area additive manufacturing (BAAM) materials. Rapid Prototyp J 23:181–189. https://doi.org/10.1108/RPJ-12-2015-0183
61. Wang Z, Smith DE, Jack DA (2021) A statistical homogenization approach for incorporating fiber aspect ratio distribution in large area polymer composite deposition additive manufacturing property predictions. Addit Manuf. https://doi.org/10.1016/j.addma.2021.102006
62. Wang Z, Smith DE (2019) Numerical analysis of screw swirling effects on fiber orientation in large area additive manufacturing polymer composite deposition. Compos Part B Eng. https://doi.org/10.1016/j.compositesb.2019.107284
63. Wang F, Fathizadan S, Ju F et al (2021) Print surface thermal modeling and layer time control for large-scale additive manufacturing. IEEE Trans Autom Sci Eng 18:244–254. https://doi.org/10.1109/TASE.2020.3001047
64. Chesser P, Post BK, Lind R, et al (2017) Changing print resolution on BAAM via Selectable Nozzles. In: Annual international

solid freeform fabrication symposium – An additive manufacturing conference. Austin, United States of America
65. Mhatre P (2019) Process Planning for Concurrent Multi-nozzle 3D Printing. rochester institute of technology
66. Chesser P, Post B, Roschli A et al (2019) Extrusion control for high quality printing on big area additive manufacturing (BAAM) systems. Addit Manuf 28:445–455. https://doi.org/10.1016/j.addma.2019.05.020
67. Layher M, Bliedtner J, Al E (2018) Conceptual development of a high-productive fabrication system for. Additive manufactured large-scale items from arbitrarily chosen plastics. In: direct digital manufacturing conference. Berlin, Germany
68. Felsch T, Klaeger U, Steuer J, et al (2017) Robotic system for additive manufacturing of large and complex parts. In: 22nd IEEE international conference on emerging technologies and factory automation. Limassol, Cyprus
69. Minjares C (2020) Development of a multi-axis wire embedding device for a large area thermoplastic pellet-fed additive manufacturing system. University of Texas at El Paso
70. Roschli A (2016) Dynamic extruder control for polymer printing in big area additive manufacturing. university of tennessee - Knoxville
71. Felber SO, Aburaia M, Wöber W, Lackner M (2021) Parameter optimization for the 3D print of thermo-plastic pellets with an industrial robot. In: Lecture Notes in Mechanical Engineering. Springer
72. Wachsmuth JP (2008) Multiple independent extrusion heads for fused deposition modeling. Virginia Tech
73. Leite M, Ventura R, Al E (2018) 3D printing of large parts using multiple collaborative deposition heads – a case study with FDM. In: 3rd International conference on progress in additive manufacturing. nanyang, Singapore
74. Sardinha M (2017) Design and development of a modular fused deposition modelling apparatus. University of Lisbon
75. Poudel L, Zhou W, Sha Z (2020) A Generative approach for scheduling multi-robot cooperative three-dimensional printing. J Comput Inf Sci Eng. https://doi.org/10.1115/1.4047261
76. Frutuoso N (2017) Tool-path Generation for a multiple independent print head system for fused deposition modeling. University of Lisbon
77. Badarinath R, Prabhu V (2021) Integration and evaluation of robotic fused filament fabrication system. Addit Manuf. https://doi.org/10.1016/j.addma.2021.101951
78. Shen H, Pan L, Qian J (2019) Research on large-scale additive manufacturing based on multi-robot collaboration technology. Addit Manuf. https://doi.org/10.1016/j.addma.2019.100906
79. Boulger AM, Chesser PC, et al (2018) Pick and Place Robotic Actuator for Big Area Additive Manufacturing. In: 29th annual international solid freeform fabrication symposium – An additive manufacturing conference. Austin United States of America
80. Roschli A, Gaul KT, Boulger AM et al (2019) Designing for big area additive manufacturing. Addit Manuf 25:275–285. https://doi.org/10.1016/j.addma.2018.11.006
81. Urbanic RJ, Hedrick R (2016) Fused deposition modeling design rules for building large, complex components. Comput Aided Des Appl 13:348–368. https://doi.org/10.1080/16864360.2015.1114393
82. Zhang Z, Poudel L, Sha Z et al (2020) Data-DRIVEN PREDICTIVE MODELING OF TENSILE BEHAVIOR OF PARTS Fabricated by Cooperative 3D Printing. J Comput Inf Sci Eng 10(1115/1):4045290
83. Sardinha M, Frutuoso N, Vicente CMS et al (2020) Influence of seams in the mechanical properties of PLA produced with multiple extrusion modules. Procedia Struct Integr 28:358–363. https://doi.org/10.1016/j.prostr.2020.10.042
84. Shah J, Snider B, Clarke T et al (2019) Large-scale 3D printers for additive manufacturing: design considerations and challenges. Int J Adv Manuf Technol 104:3679–3693. https://doi.org/10.1007/s00170-019-04074-6
85. Choo K, Friedrich B, Daugherty T et al (2019) Heat retention modeling of large area additive manufacturing. Addit Manuf 28:325–332. https://doi.org/10.1016/j.addma.2019.04.014
86. Borish M, Post BK, Roschli A et al (2020) Real-time defect correction in large-scale polymer additive manufacturing via thermal imaging and laser profilometer. Procedia Manuf 48:625–633. https://doi.org/10.1016/j.promfg.2020.05.091
87. Pourali M, Peterson AM (2019) Thermal modeling of material extrusion additive manufacturing. In: polymer-based additive manufacturing: recent developments. American chemical society 115–130
88. Alberti D (2020) Towards the design and manufacturing of products Using Large-Scale FFF Printers. University of Alberta
89. Kurfess R (2019) A thermally-driven design methodology for large-scale polymer additive manufacturing systems. Massachusetts Institute of Technology
90. Hoskins D, Kim S, Ahmed H, et al (2019) Modeling thermal expansion of a large area extrusion deposition additively manufactured parts using a non-homogenized approach. In: 30th annual international solid freeform fabrication symposium – an additive manufacturing conference. Austin, United States of America
91. Friedrich B, Choo K (2020) Thermal simulation of big area additive manufacturing. In: 7th international conference on fluid flow, Heat and Mass Transf. Virtual Conference
92. Guerguis M, Eikevik L, Obendorf A et al (2016) Algorithmic design for 3D printing at building scale. Int J Mod Res Eng Technol 1:1–10
93. Roschli AC, Borish MC, Post BK, Et A (2019) Design for slicing in large format fused filament fabrication. In: The composites and advanced materials expo. Anaheim. United States of America
94. Lee M (2019) Design for additive manufacturing (DfAM) of large size products using a plastic pellet extrusion: case study of the excavator cabin production. Ulsan national institute of science and Technology
95. Fernández E, Ayas C, Langelaar M, Duysinx P (2021) Topology optimisation for large-scale additive manufacturing: generating designs tailored to the deposition nozzle size. Virtual Phys Prototyp 16:196–220. https://doi.org/10.1080/17452759.2021.1914893
96. Dreifus GD, Jin Y, Ally N, Post BK (2016) Approaches to geometric data analysis on big area additively manufactured (BAAM) parts. In: international solid freeform fabrication symposium. Austin, United States of America
97. Silberglied C (2018) Extruder dynamics and control in large scale additive manufacturing. Georgia Institute of Technology
98. D'Amico T, Peterson AM (2020) Bead parameterization of desktop and room-scale material extrusion additive manufacturing: How print speed and thermal properties affect heat transfer. Addit Manuf 34:101239. https://doi.org/10.1016/j.addma.2020.101239
99. Fathizadan S, Ju F, Rowe K et al (2021) A novel real-time thermal analysis and layer time control framework for large-scale additive manufacturing. J Manuf Sci Eng 10(1115/1):4048045
100. Borish M, Post BK, Roschli A et al (2019) Defect identification and mitigation via visual inspection in large-scale additive manufacturing. JOM 71:893–899. https://doi.org/10.1007/s11837-018-3220-6
101. Borish M, Post BK, Roschli A et al (2019) In-situ thermal imaging for single layer build time alteration in large-scale polymer additive manufacturing. Procedia Manuf 34:482–488. https://doi.org/10.1016/j.promfg.2019.06.202

102. MacDonald E, Burden E, Walker J, et al (2017) Spatial Frequency Analysis for Improved Quality in Big Area Additive Manufacturing (BAAM). In: ASME 2017 International Mechanical Engineering Congress and Exposition. Florida, United States of America
103. Eyercioglu O, Aladag M, Sever S (2018) Temperature evaluation and bonding quality of large scale additive manufacturing thin wall parts. Sigma J Eng Nat Sci 36:645–654
104. Kishore V, Nycz A, Lindahl J, et al (2019) Effect of infrared preheating on the mechanical properties of large format 3D Printed Parts. In: international solid freeform fabrication symposium. Austin, United States of America
105. Kishore V, Ajinjeru C, Nycz A et al (2017) Infrared preheating to improve interlayer strength of big area additive manufacturing (BAAM) components. Addit Manuf 14:7–12. https://doi.org/10.1016/j.addma.2016.11.008
106. Schnittker K (2018) Evaluation Of large area additively manufactured fiber reinforced acrylonitrile butadiene styrene. The University of Texas at El Paso
107. Schnittker K, Arrieta E, Jimenez X et al (2019) Integrating digital image correlation in mechanical testing for the materials characterization of big area additive manufacturing feedstock. Addit Manuf 26:129–137. https://doi.org/10.1016/j.addma.2018.12.016
108. Bedsole R, Hill C, Kunc V, et al (2017) Structural evaluation of complex subcomponents manufactured by large scale extrusion deposition of carbon fiber reinforced aBS. In: American society for composites - thirty second technical conference. Lancaster, United States of America
109. Duty C, Ajinjeru C, Kishore V et al (2018) What makes a material printable? a viscoelastic model for extrusion-based 3D printing of polymers. J Manuf Process 35:526–537. https://doi.org/10.1016/J.JMAPRO.2018.08.008
110. Roschli AC, Duty CE, Lindahl JM, et al (2018) Increasing interlaminar strength in large scale additive Manufacturing. In: 29th international solid freeform fabrication symposium. Austin, United States of America
111. Kunc V, Kishore V, Chen X, et al (2016) High performance poly (etherketoneketone) (PEKK) composite parts fabricated using big area additive manufacturing (BAAM) processes. https://doi.org/10.2172/1343535
112. Billah KMM, Lorenzana FAR, Martinez NL et al (2020) Thermomechanical characterization of short carbon fiber and short glass fiber-reinforced ABS used in large format additive manufacturing. Addit Manuf. https://doi.org/10.1016/j.addma.2020.101299
113. Ajinjeru C, Kishore V, Chen X, et al (2016) The influence of rheology on melt processing conditions of amorphous thermoplastics for big area additive manufacturing (BAAM). In: 27th Annual international solid Freeform fabrication Symposium – An additive manufacturing conference. Austin, United States of America
114. Ajinjeru C, Kishore V, Liu P, et al (2017) Rheological evaluation of high temperature polymers to identify successful extrusion parameters. In: 28th annual international solid freeform fabrication symposium – an additive manufacturing Conference. Austin, United States of America
115. Ajinjeru C, Kishore V, Chen X et al (2019) Rheological survey of carbon fiber-reinforced high-temperature thermoplastics for big area additive manufacturing tooling applications. J Thermoplast Compos Mater 34:1443–1461. https://doi.org/10.1177/0892705719873941
116. Ajinjeru C, Kishore V, Sudbury TZ, et al (2017) The Influence of Rheology on Melt Processing Conditions of carbon fiber reinforced polyetherimide for big area additive manufacturing. In: SAMPE 2017 - Society for the advancement of material and process engineering. Seattle, United States of America
117. Ajinjeru C, Kishore V, Lindahl J et al (2018) The influence of dynamic rheological properties on carbon fiber-reinforced polyetherimide for large-scale extrusion-based additive manufacturing. Int J Adv Manuf Technol 99:411–418. https://doi.org/10.1007/S00170-018-2510-Z
118. Duty C, Failla J, Kim S, et al (2018) Z-Pinning approach for reducing mechanical anisotropy of 3D Printed Parts. In: 29th annual international solid freeform fabrication symposium – an additive Manufacturing Conference. Austin, United States of America
119. Chesser PC, Lind RF, Post BK, et al (2018) Using post-tensioning in large scale additive parts for load bearing structures. In: 29th annual international solid freeform fabrication symposium – an additive manufacturing Conference. Austin, United States of America
120. Sánchez DM, Mata M, Delgado FJ et al (2020) Development of carbon fiber acrylonitrile styrene acrylate composite for large format additive manufacturing. Mater Des. https://doi.org/10.1016/j.matdes.2020.108577
121. Peerzada M, Abbasi S, Lau KT, Hameed N (2020) Additive manufacturing of epoxy resins: materials, methods, and latest trends. Ind Eng Chem Res 59:6375–6390. https://doi.org/10.1021/acs.iecr.9b06870
122. Kunc V, Lindahl J, Mathews M, et al (2018) Low cost reactive polymers for large scale additive manufacturing. In: CAMX – The Composites and Advanced Materials Expo. Dallas, United States of America
123. Romberg SK, Hershey CJ, Lindahl JM, et al (2019) Large-scale Additive Manufacturing of Highly Exothermic Reactive Polymer Systems. In: SAMPE 2019 - Society for the Advancement of Material and Process Engineering. Soc. for the Advancement of Material and Process Engineering, Charlotte, United States of America
124. Hershey C, Lindahl J, Romberg S, et al (2019) Large-scale reactive extrusion deposition of sparse Infill structures with solid perimeters. In: CAMX – The Composites and advanced materials expo Anaheim, United States of America
125. Brackett J, Yan Y, Cauthen D et al (2021) Characterizing material transitions in large-scale additive Manufacturing. Addit Manuf. https://doi.org/10.1016/j.addma.2020.101750
126. Brackett J, Yan Y, Cauthen D, et al (2019) Development of functionally graded material capabilities in large-scale extrusion deposition additive manufacturing. In: 30th Annual international solid FREEFORM Fabrication Symposium – An Additive Manufacturing Conference. Austin, United States of America
127. Stratasys (2018) High-Quality Flying. https://www.stratasys.com/-/media/files/case-studies/aerospace/cs_fdm_ae_cea_0717aweb.pdf. Accessed 25 Jul 2022
128. Hipolite W (2015) China Eastern Airlines Successfully 3D Prints Airplane Parts for Boeing 777–300ER Aircraft. https://3dprint.com/57751/china-eastern-airlines-3d-print/. Accessed 25 Jul 2022
129. Griffiths L (2020) Additive manufacturing in the aircraft cabin. https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/additive-manufacturing-in-the-aircraft-cabin/. Accessed 25 Jul 2022
130. Diehl Aviation (2019) Diehl Aviation delivers its largest 3D-printed serial part to date. https://www.diehl.com/aviation/en/press-and-media/press/diehl-aviation-delivers-its-largest-3d-printed-serial-part-to-date/. Accessed 25 Jul 2022
131. Griffiths L (2018) How 3D printing is shaping the future of aircraft maintenance, repair & overhaul. https://www.tctmagazine.

com/additive-manufacturing-3d-printing-news/additive-manufacturing-aerospace-maintenance-repair/. Accessed 25 Jul 2022
132. Szwedziak K, Łusiak T, Bąbel R et al (2022) Wind tunnel experiments on an aircraft model fabricated using a 3d printing technique. J Manuf Mater Process 6:12. https://doi.org/10.3390/jmmp6010012
133. McLearen LJ (2015) Additive manufacturing in the Marine Corps. United States Naval Academy
134. Hiemenz J (2014) Additive manufacturing trends in aerospace. White Paper. Stratasys 1–11
135. Grady JE, Haller WJ, Poinsatte PE, et al (2015) A fully non-metallic gas turbine engine enabled by additive manufacturing Part I: System analysis, Component Identification, Additive manufacturing, and Testing of Polymer Composites. NASA Tech Reports, NASA/TM—2015–218748
136. Boissonneault T (2019) Marshall Aerospace and Defence using FDM 3D printing for flight-ready parts. https://www.3dprintingmedia.network/marshall-aerospace-defence-fdm-3d-printing/. Accessed 25 Jul 2022
137. 3D Printing Media Network (2021) Dahltram I-350CF resin helps BAE deliver parts to UK air combat. https://www.3dprintingmedia.network/airtech-dahltram-i-350cf-resin-helps-bae-deliver-parts/. Accessed 25 Jul 2022
138. Sher F (2021) Caracol 3D prints large scale aerospace tools in composites. https://www.3dprintingmedia.network/caracol-3d-prints-large-scale-aerospace-tools-in-composite-materials/. Accessed 25 Jul 2022
139. Sher D (2020) Additive Engineering Solutions 3D prints 12 foot long fixture. https://www.3dprintingmedia.network/additive-engineering-solutions-3d-prints-12-foot-long-fixture-for-dassault-falcon-jet/. Accessed 25 Jul 2022
140. Stratasys (2022) Stratasys Partners with Aurora Flight Sciences. https://www.stratasys.com/en/resources/case-studies/aurora. Accessed 25 Jul 2022
141. Thryft AR (2014) Lockheed & RedEye Team to 3D-Print Rocket Fuel Tanks. https://www.designnews.com/design-hardware-software/lockheed-redeye-team-3d-print-rocket-fuel-tanks. Accessed 25 Jul 2022
142. Pearson A (2020) United Launch Alliance moves forward with 3D printed parts, reducing production time and costs. https://www.stratasys.com/en/resources/blog/atlas-v-rocket-3d-printing/. Accessed 25 Jul 2022
143. Cross T (2018) How one rocket startup is developing 3D-printed rocket engines for testing. https://www.teslarati.com/rocket-crafters-3d-printed-engine-rd-testing/. Accessed 25 Jul 2022
144. George A (2013) 3-D Printed Car Is as Strong as Steel, Half the Weight, and Nearing Production. https://www.wired.com/2013/02/3d-printed-car/. Accessed 25 Jul 2022
145. Krassenstein B (2014) Local Motors' 3D Printed "Strati" Car Has Just Taken Its First Test Drive. https://3dprint.com/15139/local-motors-3d-printed-strati/. Accessed 25 Jul 2022
146. Blain L (2015) Local Motors' LM3D Swim set to be the world's first 3D-printed electric production car. https://newatlas.com/local-motors-lm3d-swim-3d-printed-car/40204/. Accessed 25 Jul 2022
147. Sher D (2022) The YOYO 3D printed EV by XEV is already zooming around. https://www.3dprintingmedia.network/the-yoyo-3d-printed-ev-by-xev-is-already-zooming-around/. Accessed 25 Jul 2022
148. Sher D (2020) Scaled unveils Project Chameleon 3D printed electric vehicle. https://www.3dprintingmedia.network/scaled-unveils-project-chamaleon-3d-printed-ev/. Accessed 25 Jul 2022
149. Sher D (2020) Nikola Corporation installs large format 3D printer. https://www.3dprintingmedia.network/nikola-corporation-installs-large-format-3d-printer/. Accessed 25 Jul 2022
150. Everett H (2021) BCN3D and Elisava Racing Team create DAYNA mountain rescue motorbike with 3D printing. https://3dprintingindustry.com/news/bcn3d-and-elisava-racing-team-create-dayna-mountain-rescue-motorbike-with-3d-printing-183413/. Accessed 25 Jul 2022
151. Curran S, Chambon P, Lind R, et al (2016) Big Area Additive Manufacturing and Hardware-in-the-Loop for Rapid Vehicle Powertrain Prototyping: A Case Study on the Development of a 3-D-Printed Shelby Cobra. In: SAE World Congress. Detroit, United States of MAerica
152. Chambon P, Curran S, Huff S et al (2017) Development of a range-extended electric vehicle powertrain for an integrated energy systems research printed utility vehicle. Appl Energy 191:99–110. https://doi.org/10.1016/j.apenergy.2017.01.045
153. Paukert C (2017) Ford's new room-sized 3D printer upends additive manufacturing as we know it. https://www.cnet.com/roadshow/news/fords-new-room-sized-3d-printer-upends-additive-manufacturing-as-we-know-it/. Accessed 25 Jul 2022
154. Jafferson JM, Sharma H (2021) Design of 3D printable airless tyres using NTopology. Mater Today Proc 46:1147–1160. https://doi.org/10.1016/j.matpr.2021.02.058
155. Chesser P, Love L, Atkins C et al (2021). Comparison of Polymer AM Technologies for Automotive Tooling for Composite Engines. https://doi.org/10.2172/1761614
156. Love LJ, Noakes MW, Post BK et al (2018). Feasibility of Using Additive Manufacturing to Produce Automotive Tooling. https://doi.org/10.2172/1463997
157. Henderson HB, Stromme ET, Kesler MS et al (2020) Additively manufactured single-use molds and reusable patterns for large automotive and hydroelectric components. Int J Met 14:356–364. https://doi.org/10.1007/s40962-019-00379-0
158. Ziółkowski M, Dyl T (2020) Possible applications of additive manufacturing technologies in shipbuilding: a review. Machines 8:84. https://doi.org/10.3390/machines8040084
159. Sher D (2021) Drone 3D printing is taking off targeting mass production. https://www.3dprintingmedia.network/drone-mass-production-is-taking-off-with-3d-printing/. Accessed 25 Jul 2022
160. Post BK, Chesser PC, Lind RF et al (2018). Feasibility of using Big Area Additive Manufacturing to Directly Manufacture Boat Molds. https://doi.org/10.2172/1427645
161. Shoemaker S (2016) First-ever 3D printed excavator project advances large-scale additive manufacturing R&D. https://www.ornl.gov/blog/first-ever-3d-printed-excavator-project-advances-large-scale-additive-manufacturing-rd. Accessed 25 Jul 2022
162. Vicente CMS, Sardinha M, Frutuoso N, Leite M (2022) Big FDM Project - DamDikeCare Case Study
163. Burke JJ (2019) ORNL and University of Maine collaboration launches 3D printing with wood products. https://www.ornl.gov/blog/ornl-and-university-maine-collaboration-launches-3d-printing-wood-products. Accessed 25 Jul 2022
164. Zhao X, Tekinalp H, Meng X et al (2019) Poplar as biofiber reinforcement in composites for large-scale 3D printing. ACS Appl Bio Mater 2:4557–4570. https://doi.org/10.1021/acsabm.9b00675
165. Ryder G, Ion B, Green G et al (2002) Rapid design and manufacture tools in architecture. Autom Constr 11:279–290. https://doi.org/10.1016/S0926-5805(00)00111-4
166. Bos F, Wolfs R, Ahmed Z, Salet T (2016) Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. Virtual Phys Prototyp 11:209–225. https://doi.org/10.1080/17452759.2016.1209867
167. BCN3D (2018) Architects pay tribute to Calatrava with a 3D printed architectural model. https://www.bcn3d.com/calatrava-3d-printed-turning-torso/. Accessed 25 Jul 2022

168. BigRep (2018) Villa Ancora - 3D Printed Architectural Model. https://bigrep.com/ebooks/villa-ancora-3d-printed-architectural-model/. Accessed 25 Jul 2022
169. Hager I, Golonka A, Putanowicz R (2016) 3D Printing of buildings and building components as the future of sustainable construction? Procedia Eng 151:292–299. https://doi.org/10.1016/j.proeng.2016.07.357
170. Biswas K, Lind R, Al E (2016) Big Area Additive Manufacturing Applied to Buildings. In: Thermal Performance of the Exterior Envelopes of Whole Buildings XIII International Conference. Florida, United States of America
171. Desmond R (2014) Chinese Create Huge 40×40 Foot Graphene/Fiberglass 3D Printer – Planning on Constructing Homes. https://3dprint.com/7181/china-huge-3d-printer/. Accessed 25 Jul 2022
172. Love LJ, Roschli AC, Post BK, Gaul KT (2018) Explore the techno-economic viability of using large-scale additive manufacturing (AM) For high-performance windows. https://doi.org/10.2172/1479724
173. Rebaioli L, Magnoni P, Fassi I et al (2019) Process parameters tuning and online re-slicing for robotized additive manufacturing of big plastic objects. Robot Comput Integr Manuf 55:55–64. https://doi.org/10.1016/j.rcim.2018.07.012
174. Love L, Post B, Roschli A, et al (2019) Feasibility of using baam for mold inserts for the precast concrete industry (CRADA NFE-17–06874 Final Report). https://doi.org/10.2172/1606893
175. Lloyd's Register Energy (2014) The opportunities for additive manufacturing in the energy industry
176. Abdelrahman A, Johnson DA (2014) Development of a wind turbine test rig and rotor for trailing edge flap investigation: static flap angles case. J Phys Conf Ser. https://doi.org/10.1088/1742-6596/524/1/012059
177. Post BK, Chesser PC, Roschli AC et al (2018). Large-Scale Additive Manufacturing for Low Cost Small-Scale Wind Turbine Manufacturing. https://doi.org/10.2172/1493993
178. Richardson B, Roschli A, Noakes M (2018) BAAM Additive manufacturing of a building integrated wind turbine for mass production (CRADA FINAL REPORT NFE-17–06605)
179. Kim S, Dreifus GD, Beard B, et al (2018) Graded infill structure of wind turbine blade accounting for internal stress in big area additive manufacturing. In: CAMX – The composites and advanced materials Expo. Dallas, United States of America
180. Sanandiya ND, Vijay Y, Dimopoulou M et al (2018) Large-scale additive manufacturing with bioinspired cellulosic materials. Sci Reports 81(8):1–8. https://doi.org/10.1038/s41598-018-26985-2
181. Mann M, Palmer S, Lee D et al (2017). The Current State of Additive Manufacturing in Wind Energy Systems. https://doi.org/10.2172/1415918
182. Chesser P, Love L, Witt AM, Roos P (2020) Feasibility of using additive manufacturing to produce axial flow hydropower turbine housing. Runner, and Draft Tube. https://doi.org/10.2172/1763463
183. Post BK, Roschli AC, Heineman J, et al (2020) Utility of big area additive manufacturing for part production for low-head hydropower (CRADA NFE-18–07280 Final Report). https://doi.org/10.2172/1747020
184. Paranthaman MP (2016) Fabrication of large area printable composite magnets (CRADA/NFE-15–05779 Report). https://doi.org/10.2172/1329774
185. Gandha K, Li L, Nlebedim IC et al (2018) Additive manufacturing of anisotropic hybrid NdFeB-SmFeN nylon composite bonded magnets. J Magn Magn Mater 467:8–13. https://doi.org/10.1016/j.jmmm.2018.07.021
186. Post BK, Lind R, Love LJ, et al (2017) Big area additive manufacturing application in wind turbine molds. In: 28th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference. Austin, United States of America
187. Post B, Richardson B, Lloyd P, et al (2017) Additive Manufacturing of Wind Turbine Molds
188. Cardeal G, Sequeira D, Mendonça J et al (2021) Additive manufacturing in the process industry: a process-based cost model to study life cycle cost and the viability of additive manufacturing spare parts. Procedia CIRP 98:211–216. https://doi.org/10.1016/j.procir.2021.01.032
189. Cardeal G, Ferreira B, Peças P et al (2022) Designing sustainable business models to reduce spare part inventory. Procedia CIRP 105:171–176. https://doi.org/10.1016/j.procir.2022.02.029
190. Heinen JJ, Hoberg K (2019) Assessing the potential of additive manufacturing for the provision of spare parts. J Oper Manag 65:810–826. https://doi.org/10.1002/joom.1054