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ORIGINAL ARTICLE

Additive manufacturing and its societal impact: a literature review

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Abstract Thirty years into its development, additive manufacturing has become a mainstream manufacturing process. Additive manufacturing build up parts by adding materials one layer at a time based on a computerized 3D solid model. It does not require the use of fixtures, cutting tools, coolants, and other auxiliary resources. It allows design optimization and the producing of customized parts on-demand. Its advantages over conventional manufacturing have captivated the imagination of the public, reflected in recent mainstream publications that call additive manufacturing "the third industrial revolution." This paper reviews the societal impact of additive manufacturing from a technical perspective. Abundance of evidences were found to support the promises of additive manufacturing in the following areas: (1) customized healthcare products to improve population health and quality of life, (2) reduced environmental impact for manufacturing sustainability, and (3) simplified supply chain to increase efficiency and responsiveness in demand fulfillment. In the mean time, the review also identified the need for further research in the areas of life-cycle energy consumption evaluation and potential occupation hazard assessment for additive manufacturing.

Keywords Additive manufacturing · Environmental impact · Energy consumption · Supply chain · Health and wellbeing

1 Introduction

Additive manufacturing (AM) is the "process of joining materials to make objects from 3D model data, usually layer upon layer" [1]. It is also known as rapid manufacturing [2] or rapid prototyping [3]. Unlike conventional manufacturing techniques such as machining and stamping that fabricate products by removing materials from a larger stock or sheet metal, additive manufacturing creates the final shape by adding materials. It has the ability to make efficient use of raw materials and produce minimal waste while reaching satisfactory geometric accuracy [1–3]. Using additive manufacturing, a design in the form of a computerized 3D solid model can be directly transformed to a finished product without the use of additional fixtures and cutting tools. This opens up the possibility of producing parts with complex geometry that are difficult to obtain using material removal processes. As such, it is unnecessary to consider design for manufacturing and assembly (DFM/DFA) principles in product design, which is conducive to design innovation.

AM enables environmental friendly product design as well. Unlike traditional manufacturing processes that place many constraints on product design, the flexibility of AM allows manufacturers to optimize design for lean production, which by its nature eliminates waste [4]. In addition, AM's ability to construct complex geometries means that many previously separated parts can be consolidated into a single object. Furthermore, the topologically optimized designs that AM is capable of realizing could increase a product's functionality, thus reducing the amount of energy, fuel, or natural resources required for its operation [5].

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The development of additive manufacturing technology started in the 1980s [6]. Significant progress has been made since then, and there is an expectation that additive manufacturing technology can revolutionize the manufacturing industry and provide various benefits to the society at large. These benefits include:

- Healthcare products customized to the needs of individual consumers, which is expected to significantly improve population wellbeing.
- Reduced raw material usage and energy consumption, which is a key contribution to environmental sustainability.
- On-demand manufacturing, which presents an opportunity to reconfigure the manufacturing supply chain to bring cheaper products to consumers faster while utilizing fewer resources.

Although a large number of papers pertaining to additive manufacturing have been published over the past three decades, most of them focused on various processing technologies. Recently, some researchers started investigating system-level issues in additive manufacturing. For example, a group of researchers at Loughborough University has been exploring the use of additive manufacturing to achieve low-carbon design, manufacturing, and service for several years [7]. Issues related to the societal impact of additive manufacturing have also been discussed. However, such information is scattered in various publications with different technical focuses. The objective of this paper is to gather, analyze, categorize, and summarize information pertinent to the societal impact of additive manufacturing. The paper is organized as follows. Section 2 provides a brief introduction of additive manufacturing and its characteristics. Section 3 investigates the impact of additive manufacturing on population health and wellbeing. Section 4 discusses the environmental impact of additive manufacturing. Section 5 explores the possibility of revolutionizing the delivery of additively manufactured products through supply chain reconfiguration. Section 6 discusses the potential occupational hazards of additive manufacturing. Finally, a summary analysis is presented in Section 7.

2 Additive manufacturing technology

AM technology consists of three basic steps:

(1) A computerized 3D solid model is developed and converted into a standard AM file format such as the traditional standard tessellation language format [8] or the recent additive manufacturing file format [9].
(2) The file is sent to an AM machine where it is manipulated, e.g., changing the position and orientation of the part or scaling the part.
(3) The part is built layer by layer on the AM machine.

Different AM processes build and consolidate layers in different ways. Some processes use thermal energy from laser or electron beams, which is directed via optics to melt or sinter (form a coherent mass without melting) metal or plastic powder together. Other processes use inkjet-type printing heads to accurately spray binder or solvent onto powdered ceramic or polymer. Major AM processes are briefly summarized as follows:

- *Fused deposition modeling (FDM)*. The patent for FDM (US Patent 5121329) was awarded on June 9, 1992, but the technique was described earlier in Crump [10]. Liquid thermoplastic material is extruded from a movable FDM head and then deposited in ultra-thin layers onto a substrate. The material is heated to 1 °C above its melting point so that it solidifies almost immediately after extrusion and cold welds to the previous layers. The materials used have since been expanded to include wax, metals, and ceramics [3]. Machines with two nozzles have also been developed, one for part material and the other for support material that is cheaper and breaks away from the part without impairing its surface [11]. A good variety of materials can be used in FDM and the part accuracy can reach ±0.05 mm. FDM equipment has a compact size, and the maintenance cost is low. However, FDM has some disadvantages, e.g., the seam line between layers, the required supports, long build time, and delamination caused by temperature fluctuation [12].
- *Inkjet printing (IJP)*. Ink jet is a non-impact dot-matrix technology originally developed for printing 2D images. Its origin can be traced to the late nineteenth century and the first patent (US Patent 2566443) for practical inkjet device was awarded on September 4, 1951 [13]. IJP uses liquid phase materials, or inks, that consist of a solute dissolved or dispersed in a solvent. A fixed quantity of ink in a chamber is ejected from a nozzle through a sudden, quasi-adiabatic reduction of the chamber volume via piezoelectric action. The ejected droplet falls under action of gravity until it impinges on the substrate and then dries through solvent evaporation. Printing of a 3D part involves the use of pre-patterned substrates at multiple layers of processing. Various types of materials have been used in IJP to produce a variety of products including solar cells, sensors, and thin-film transistors [14]. IJP can achieve faster response and just-in-time customization. Its disadvantages include fragile print heads (that is prone to clogging or blockage) and expensive ink cartridges.
- *Laminated object manufacturing (LOM)*. The patent for LOM (US Patent 4752352) was awarded on June 21, 1988. A simpler process was presented in Feygin and Hsieh [15]. LOM use adhesive-coated sheet materials. The adhesive, which can be pre-coated onto materials or be deposited prior to bonding, allows the sheets to be

attached to each other. 3D parts are then manufactured by sequentially laminating and cutting 2D cross-sections. The cutting is done using laser beam where its velocity and focus is adjusted so that the cutting depth corresponds exactly to the thickness of the layer, thus avoid damaging the underlying layers. A variety of materials can be used, including paper, metals, plastics, fabrics, synthetic materials, and composites. The LOM process is inexpensive and no toxic fumes are generated. It can also be automated with little operator attention. However, LOM has some *Z*-axis accuracy problems which results in dimensional stability issues. It may generate some internal cavities which affect product quality. In addition, postproduction time is needed to eliminate waste and in some cases secondary processes are required to generate accurately functional parts [16].

- *Laser engineered net shaping (LENS)*. The LENS technology was originally developed at Sandia National Laboratories in collaboration with Pratt & Whitney and then licensed to Optomec Inc. in 1997 [17]. The patent (US Patent 6046426) was awarded on April 4, 2000. With LENS, a part is fabricated by focusing a high-powered laser beam onto a substrate to create a molten pool in which metal powder particles are injected to build each layer. The substrate is moved beneath the laser beam to deposit a thin cross-section to create the desired geometry. Consecutive layers are sequentially deposited to build a 3D part. With appropriate control of fabrication parameters, desired geometric properties (accuracy and surface finish) and material properties (strength and ductility) of a part can be achieved [18]. LENS can be used to repair parts as well as fabricate new ones. It does not require secondary firing operations. However, LENS still needs postproduction process and the part must be cut from the build substrate. It also has a rough surface finish which may require machining or polishing.
- *Stereolithography (SLA)*. The patent for SLA (US Patent 4575330) was awarded on March 11, 1986 and the technique was publicized in Hull [19]. SLA uses a photosensitive monomer resin and a UV laser to build parts one layer at a time. It requires support structures to attach the part to the build platform. On each layer, the laser beam traces the cross-section of the part on the surface of the liquid resin to solidify the pattern. The build platform is then lowered in order to coat the part thoroughly. It is then raised to a level such that a blade wipes the resin, leaving exactly one layer of resin above the part. The part is then lowered by one layer and left until the liquid has settled to ensure an even surface before the next layer is built [20]. Once the part is completed, the support structures may be removed manually. SLA is particularly suitable in the manufacturing industry as it lessens the time it takes for a prototype part to be produced and can achieve a good surface finish. The main limitation of SLA is that the product size is relatively small, roughly no larger than a 2-foot cube. Another disadvantage is the cost. The photopolymer alone costs \$300 to \$500, not to mention the machine itself. Also, the materials used in SLA are relatively limited compared to other AM processes [21].
- *Selective laser sintering (SLS)*. The patent for SLS (US Patent 4863538) was awarded on September 5, 1989, but the process was described earlier in Deckard and Beaman [22, 23]. SLS uses a high power laser to fuse small particles of the build material (polymers, metals, ceramics, glass, or any material that can be pulverized). The fabrication powder bed is heated to just below the melting point of the material to minimize thermal distortion and facilitate fusion to the previous layer. Each layer is drawn on the powder bed using the laser to sinter the material. The sintered material forms the part whilst the un-sintered powder remains in place to support the structure and may be cleaned away and recycled once the build is complete. SLS offers the freedom to quickly build complex parts that are more durable and provide better functionality over other AM processes. No post curing is required, and the build time is fast. However, SLS operation is complicated as many build variables need to be decided. The achievable surface finish is not as good as that from SLA, and the material changeover is difficult [16].
- *Three-dimensional printing (3DP)*. The patent for 3DP (US Patent 5204055) was awarded on April 20, 1993, but the work was reported earlier in Sachs et al. [24]. 3DP functions by the deposition of powdered material on a substrate that are selectively joined using a binder sprayed through a nozzle. The material is first stabilized through misting with water droplets to avoid excessive disturbance when it is hit by the binder. Following the sequential application of layers, the unbound powder is removed. The part may be further processed by subjecting it to a firing at high temperature to further strengthen the bonding. This process may be applied to the production of metal, ceramic, and metal/ceramic composite parts. 3DP offers the advantage of speedy fabrication and low materials cost [25]. In fact, it is probably the fastest of all AM processes. However, there are some limitations, such as rough surface finish, size limitation, and high cost.

Note that the AM process of solid ground curing (SGC) ceased to be used in 1999 [2] and hence is not included in the previous summary. The disappearance of SGC is due to the fact that the production system was very complex and therefore suffered from high initial and operating costs.

Compared to conventional manufacturing processes, AM processes have the following perceived advantages:

- *Material efficiency*. Unlike conventional subtractive manufacturing where large amount of materials need to be removed, AM uses raw materials efficiently by building parts layer by layer. Leftover materials can often be reused with minimum processing.

- *Resource efficiency*. Conventional manufacturing processes require auxiliary resources such as jigs, fixtures, cutting tools, and coolants in addition to the main machine tool. AM does not require these additional resources. As a result, parts can be made by small manufacturers that are close to customers. This presents an opportunity for improved supply chain dynamics.
- *Part flexibility*. Because there are no tooling constraints, parts with complex features can be made in a single piece. In other words, there is no need to sacrifice part functionality for the ease of manufacture. In addition, it is possible to build a single part with varying mechanical properties (flexible in one part and stiffer in another part). This opens up opportunities for design innovation.
- *Production flexibility*. AM machines do not require costly setups and hence is economical in small batch production. The quality of the parts depends on the process rather than operator skills. As such, production can be easily synchronized with customer demand. In addition, the problems of line balancing and production bottlenecks are virtually eliminated because complex parts are produced in single pieces.

However, AM technology still cannot fully compete with conventional manufacturing, especially in the mass production field because of the following drawbacks [26]:

- *Size limitations*. AM processes often use liquid polymers, or a powder comprised of resin or plaster, to build object layers. These materials render AM unable to produce large-sized objects due to lack of material strength. Large-sized objects also often are impractical due to the extended amount of time need to complete the build process.
- *Imperfections*. Parts produced using AM processes often possess a rough and ribbed surface finish. This appearance is due to plastic beads or large-sized powder particles that are stacked on top of each other, giving the end product an unfinished look.
- *Cost*. AM equipment is considered an expensive investment. Entry level 3D printers average approximately $5,000 and can go as high as $50,000 for higher-end models, not including the cost of accessories and resins or other operational materials.

Researchers have been working on improving AM processes to overcome the abovementioned drawbacks. Nonetheless, it is unlikely that AM technology will make traditional manufacturing processes obsolete. However, it is reasonable to expect that AM processes will play an increasingly important role in manufacturing as a complementing technology.

3 Impact on population health and wellbeing

Easy access to vaccines, increased availability of medicine, and breakthrough advances in surgical procedures and therapeutic techniques have improved the general quality of life of the people around the world after World War II. A direct consequence has been the reduction in mortality rate and increased life expectancy in both developed and developing countries. The global population has increased steadily, and the population is aging. In 2006, almost 500 million people worldwide were 65 and older. This number is projected to increase to 1 billion by 2030 [27]. Caring for an increasing aging population has put significant strain on government budget world-wide. An Organization for Economic Co-operation and Development study found that the share of total health expenditure attributed to people aged 65 and over ranged from 32 to 42 %, compared with their population share of 12 to 18 % [28]. Under such circumstances, delivering high quality, economically efficient healthcare to improve the health and wellbeing of the entire population has become one of the key societal challenges in the twenty-first century.

A promising approach to deliver high-quality and economically efficient healthcare is personalized care that tailors to specific characteristics and needs of patients. This concept is fairly broad, which ranges from providing long-term care tailored to the wants and needs of elderly [29] to the use of a patient's biological data to determine the best course of therapy [30]. AM technology is well suited to produce customized products that meet individual needs and hence can play a significant role in personalized healthcare. Specifically, it has been used to produce customized surgical implants and assistive devices for improved health and wellbeing of the general population.

AM technology can be used to make custom surgical implants in a solid or resorbable material. The need for surgical implants has been increasing. For example, in 2001, almost 20,700 Americans underwent chin augmentation surgery, up a staggering 71 % compared to the previous year. Similarly, the need for lip augmentation went up 49 %, whereas the need for cheek implant went up 47 % [31]. The basic idea of making custom surgical implants is to use computer tomography scan to obtain patient specific data, from which a solid model of the required implant is developed through reverse engineering. The model is then used to build a customized implant for the patient using appropriate materials. Singare et al. [32] reported that this approach can produce very accurate implants that function well and in the meantime have aesthetical appeal. In addition, such an approach can significantly shorten the design cycle and delivery lead time of custom fit surgical implants [33]. Custom implants produced using AM technology have been used for a variety of applications including skull ([32, 34–36]), knee joint [37], elbow [38], and hip joint [39]. The most common application is probably that of dentistry, where an excellent review paper is available [40] and the information will not be repeated here. In fact, a variety of commercial dentistry products based on AM technology are now available, such as bridges and crowns offered by the Sirona group (Salzburg, Austria) and Invisalign clear dental braces offered by Align Technology (San Jose, CA). Another application area where AM products are commercially available is that of custom hearing aids where such products are offered by Minerva Laboratories (Cardiff, UK) and Phonak (Stafa, Switzerland).

AM technology can also be used to produce custom-fit safety equipment using light weight materials. Safety equipment such as helmets and protective garments is an important aspect of occupational safety and health. These devices are essential to protect professionals such as firefighters, policemen, construction workers, and athletes from potential bodily harms. Safety equipment produced using AM technology has the potential to provide excellent protection without sacrificing personal comfort of the user. As a result, the user can achieve a high level of performance while receiving maximum protection. An example is the SCUTA project conducted at Loughborough University where AM technology is used to produce personal protective equipment [41]. The goal is to tailor protective sports garments to individual athletes by taking into account variations in size and shape of different individuals. The garments can be produced in one-piece that fit the body perfectly without the need for seams or joins. They can also be optimized to reduce the specific impacts that the athletes are exposed to.

Researchers have also explored the use of AM technology to produce scaffolds for tissue engineering applications and drug delivery devices. A summary of these research works can be found in Giannatsis and Dedoussis [42]. Note that these applications have not reached the stage of commercialization. Nonetheless, the potential of AM technology to transform population health care has been recognized. This is evident from the ambitious CUSTOM-FIT European initiative that aimed to create a fully integrated system for the design, production, and supply of individualized medical and consumer goods products [43]. The initiative is driven by AM technology and is expected to have a major beneficial impact on the quality of life of European citizens.

4 Energy consumption and environmental impact

Manufacturing of goods requires energy. Industrial energy demand is one-third of the total consumption in the USA. Over the past 30 years, US industry has achieved 50 % reduction in energy intensity, i.e., the amount of energy it takes to produce $1 of goods. Roughly half of the reduction was attributed to energy efficiency improvements. The other half was a result of structural changes including the changes in product mix and off-shoring the manufacture of energy intensive products [44]. Although US manufacturers were successful in reducing energy intensity, a closer look at electricity use per unit of material processed has revealed an alarming trend. The study, conducted by Gutowski et al. [45], showed that new manufacturing processes were capable of working to finer dimensions and smaller scales but at lower rates, which resulted in very large specific electrical work requirements. It has also been observed that these new processes make more use of high-exergy value materials in very inefficient ways. The authors acknowledged that such processes could produce products with longer useful life and/or lower energy consumption during the use phase. Nonetheless, they stated that "the seemingly extravagant use of materials and energy resources by many newer manufacturing processes is alarming and needs to be addressed…." Therefore, although AM is perceived to have a positive impact on energy consumption and the environment, it is necessary to conduct a more thorough analysis.

Conducting energy consumption and environmental impact analysis for AM processes is a challenging but necessary task. Although environmentally conscious manufacturing has received increasing interest since the 1990s, there is not a uniformly satisfactory quantitative method to evaluate the environmental impacts of manufacturing processes, let alone AM. The environmental analysis for manufacturing processes should include process time, energy utilization, primary flow of work-piece materials, and secondary flows of process catalysts, as shown in Fig. 1 [46, 47, 50].

Based on the theory of industrial ecology, there are two major methods for environmental impact assessment, namely, environmental impact assessment (EIA) and life-cycle analysis (LCA). However, these methods often cannot measure the actual environmental impacts directly, predict effects, or represent causal linkages with specific effects. In addition, weighting factors are normally given in a descriptive language, such as "low," "moderate," and "serious" which is difficult if not impossible to transform into numbers and solve mathematically [48, 49]. Some researchers [49] tried to set up a quantitative model for LCA or EIA, but more work and scientific evidence is needed to determine its performance, correctness, and practicality.

Coming back to the EIA of AM processes, the common opinion is that AM has some good environmental characteristics [51]. These characteristics are summarized in Table 1. By utilizing only the amount of materials needed for the product, AM technologies have the potential to reduce lifecycle material mass and energy consumed relative to conventional subtractive manufacturing techniques by eliminating engineered scrap and the use of harmful ancillary process inputs. The pollution of terrestrial, aquatic, and atmospheric

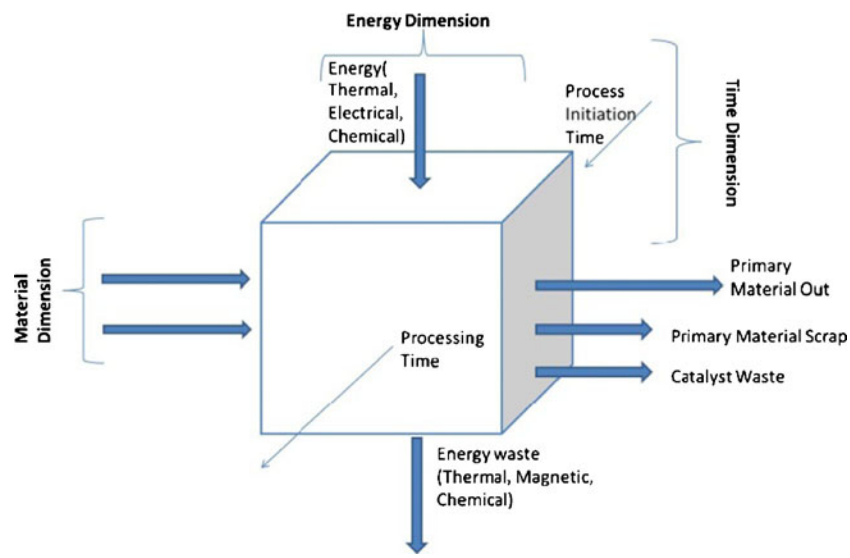

Fig. 1 Environmental analysis for manufacturing processes (modified from [46, 47])

systems is much less in AM than in conventional manufacturing processes. AM processes require no cutting fluids, which are the main source of hazard in the manufacturing waste streams [51]. Serres et al. [52] carried out an environmental assessment of direct additive laser manufacturing (CLAD, Construction Laser Additive Directe in French) process, with a life-cycle inventory as large as possible and to compare its environmental impact with conventional machining. The experimental results showed that the total environmental impact was much greater in the case of machining. CLAD process is much more environmentally friendly, with an impact reduction of about 70 %. Comparative studies were carried out in LENS [53] and Direct Metal Deposition [54, 55] with similar results.

However, comparing with conventional manufacturing processes, AM processes have their unique features in terms of system complexity and operating style. A comprehensive comparison of AM and other manufacturing processes in terms of energy usage, water usage, landfill usage, and the use of virgin materials was conducted under the ATKINS project [7]. The result is summarized in Table 2. Although AM has clear advantages in terms of environmental impact, its energy consumption far exceeds that of casting. This may come as a shock to some researchers.

The perception that AM consumes less energy than conventional manufacturing processes may be misplaced. A possible cause could be due to the way that energy consumption is measured. A measure commonly used is energy consumption rate, namely, the kilowatt hours (kWh) consumed per kilogram of part geometry produced. Using this measure, Luo et al. [51] analyzed three typical AM processes, namely, SLA, SLS, and FDM. Sreennivasan and Bourell [56] studied the performance of SLS HiQ equipment with similar method and measured its mean power consumption as 19.6 kWh. In the most recent literature, Baumers et al. [57] studied the energy consumption rates of two SLS platform: Sinterstation HiQ+Hs and EOSINT P 390. Table 3 summarizes results reported by these researchers. One can see that there are significant variations of energy consumption rates for the same AM process. It is unlikely that these variations are solely caused by the types of equipment used. Rather, most of the variations may be attributed to the way the experiments are conducted. For example, in the experiment conducted by Baumers et al. [57], the measured energy consumption rates of SLS were higher than expected as extra energy consumptions occured in the equipment warm-up and cool-down stages. It is possible that the pure AM building process is not energy intensive. However, once the entire operating procedure is considered, AM might not have an edge over traditional manufacturing processes in terms of energy consumption. Because the literature on this topic is limited, no firm conclusion can be drawn at this time.

5 Impact on manufacturing supply chain

Manufacturing and delivering products to customers require the efforts of various companies that form the manufacturing supply chain. These companies may include raw material suppliers, component suppliers, original equipment manufacturers, wholesalers/distributors, logistics service providers, and retailers. In a supply chain, materials flow forward from suppliers through various stages toward customers, whereas information and funds flow backward. It has been pointed out that AM has the potential to reduce the number of stages in the traditional supply chain [58]. Specifically, AM technology offers two opportunities: (1) to redesign products with fewer components and (2) to manufacture products near the customers (i.e., distributed manufacture). The net effect is the reduction in the need for warehousing, transportation, and packaging.

Table 1 Contrast between traditional machining and different AM processes

Technique	Acronym	Raw material	Energy Consumed	Fixture and tooling	Laser used	Solid residues	Liquid residues	Aerosol residues	Disposal
Machining		Steel, aluminum, alloy	Mechanical energy	Yes	No	Tool scrap, Chips	Fluid mix (cutting, cooling)	Tool particulate, fluid vapor	Landfill, recycling
Stereolithography	SLA	Liquid photopolymer	UV laser beam	No	Yes	Small amount of resin, removed supports	No	No	Incineration,landfill
Selective laser sintering	SLS	Nylon, metal, ceramic, paraffin wax	High power laser beam	No	Yes	Material chips	No	No	Incineration, landfill, recycling
Fused deposition modeling	FDM	Nylon, ABS, ceramic, investment casting wax, alloy	Heat	No	No	Material chips, removed supports	No	No	Incineration, landfill, recycling
Laser engineered net shape	LENS	Metal, binder	High-power laser beam	No	Yes	Material chips	No	No	Incineration, landfill, recycling
Laminated object manufacturing	LOM	Paper, polymer, metal, ceramic,	High power laser beam, heat	No	Yes	Material chips	No	No	Incineration, landfill, recycling
Inkjet printing	IJP	Liquid materials, ink	Piezoelectric nozzle	No	No	Microchips, removed supports	No	No	Incineration, landfill, recycling
Three-dimension printing	3DP	Metal, ceramic, binder	Piezoelectric nozzle, heat	No	No	Removed supports, material chips	No	No	Incineration, landfill, recycling

Tuck et al. [59] discussed how AM technology could change supply chain management thinking. First, AM can improve the efficiency of a lean supply chain through just-in-time (JIT) manufacture and waste elimination. Because AM only requires 3D data and raw materials in order to produce a complex part, it will reduce setup and changeover time, and the number of assemblies. This in turn results in a reduction of material distribution and inventory holding for work in progress. It is also possible to implement JIT manufacture at the shop floor instead of JIT delivery by suppliers to the shop floor. As a result, non-value added activities such as material movement and inventory holding can be reduced to a minimum. The result is a lean supply chain with low cost. Second, AM can improve the responsiveness of an agile supply chain. A build-to-order strategy can be implemented to ensure that no stockout would occur. The overriding cost for AM production is not labor but the machines and raw materials, which makes it economical to locate production facilities near the end customers. In addition, it is possible to customize products to meet individual customer needs. This will facilitate the implementation of a build-to-order strategy and increase responsiveness.

Several researchers have investigated the use of AM technology in the spare parts supply chain [60–62]. The spare parts supply chain in the aircraft industry faces significant challenges of providing fast repair and maintenance services while minimizing costs. A large commercial airplane is made up of several million parts. Most parts are infrequently needed, but they have to be kept in stock in order to ensure fast service time. The current supply chain for aircraft spare parts functions as follows. A safety stock of standard replacement parts is kept at the airline's warehouse. These parts can be ordered at regular intervals according to a maintenance plan. Other less frequently used parts are purchased from suppliers and often require a 24-h delivery time to ensure fast service. Therefore, suppliers must keep these parts in stock and use an overnight delivery service. To keep the stock of these slow moving (i.e., infrequently demanded) parts as low as possible, the strategy of demand aggregation is used which requires central warehousing. The trade-off is increased delivery cost. Another problem is related to the production batch size of these parts. Current production technology requires parts to be produced in large batch size to take advantage of economy of scale. However, for slow moving parts, this means a large amount of capital is tied up in the form of inventory. AM technology obvious has the potential to solve this problem. However, because AM technology is still in its developmental stage, only a limited range of parts can be produced economically. Therefore, it is necessary to use a systematic step-by-step procedure to determine suitable applications. The decisions should be revisited periodically because AM technology is constantly evolving. Detailed discussion of this procedure can be found in [62].

Table 2 Comparison of energy use and environmental impact of different manufacturing techniques under the ATKINS project

Process	Energy use (kg CO_2 per component)	Water usage (kg per component)	Landfill waste (kg)	Virgin material use (kg per component)	Hazardous waste (kg per component)
Casting	1.9	0	N/A	2	N/A
Flexline machining	2.4	0.08	1.512 (waste can be recycled)	2 (from casting)	0.0064ii
Clean machining	N/a	0.15	N/A	N/A	N/A
AM	13.15	0	0	0.65	0

Hasan and Rennie [61] noted that a fully functional AM supply chain is not yet available in the spare parts industry. The authors proposed a business model to enable such a supply chain. The model is based on an e-business platform that provides the following services:

- Sourcing: give buyers easy access to a pool of suppliers.
- Demand identification: assist suppliers to identify customers and their demand.
- Content display: provide an e-catalogue to display the products and services provided by the suppliers
- Transaction: enable the exchange of procurement information between the buyers and suppliers.
- Promotion: help suppliers advertise their products and services

Holmstrom et al. [60] proposed two different approaches to integrate AM technology in the spare parts supply chain. The first approach is to use centralized AM capacity to replace inventory holding. AM machines are deployed in centralized distribution centers to produce slow-moving spare parts on demand. Producing parts in a centralized location has the advantage of aggregating demand from various regional service locations to ensure that the investment in AM capacity is well utilized. The disadvantage is that the produced parts need to be shipped to the service locations, which results in the increase of response time. For certain parts that are needed in the first line maintenance, inventory still needs to be carried in the service locations. The centralized approach is desirable when parts that can be produced using AM are limited and the required response time is not critical. The second approach, distributed AM deployed at each service location, is suitable when the demand of AM producible parts is sufficiently high to justify the capacity investment. The advantage is the elimination of inventory holding and transportation costs and a fast response time. In addition to these two approaches, Holmstrom et al. also contemplated the feasibility of mobile AM but conceded that there are many challenges. The authors further discussed the trade-off between batch production and on-demand production, and that between specialized and general purpose AM. The key variables considered are materials and production costs, distribution and inventory obsolescence costs, and life-cycle costs for the user. They concluded that on-demand and centralized production of spare parts is most likely to succeed.

Although AM technology has yet to be truly incorporated into the spare parts supply chain, it has been successfully used to supply certain consumer goods. Reeves [63] described four such businesses: (1) Fabjectory that enables players of Second Life to purchase models of individualized avatar characters, (2) FigurePrints that allows players of World-of-Warcraft to order 1/16th scale models of their online gaming characters, (3) Landprint that offers personalized 3D model of any place on earth, and (4) Jujups that offers a range of personalized gifts such as photo frames, badges, mugs, and even chocolate. It appeared that Fabjectory has since gone out of business, but the other three are doing quite well. With this type of business model, retailers do not carry any inventory. Goods are produced on-demand either in-house or through subcontract to a third-party manufacturer and then shipped directly to the customers. There is no need for warehousing and distribution, although the final products still need to be shipped to customers. It is possible that this consumer goods supply chain can be further simplified when AM technology matures to the stage where inexpensive personal 3D printer becomes a reality. Customers can design their own personalized products or obtain files of standard products online through a technology service provider. The products can then be built right in front of the customers using their personal 3D printer. This scenario is not far-fetched. In 2004, Idealab launched the Desktop Factory to bring affordable 3D printers to the mass. In 2009, the assets of Desktop Factory were acquired by 3D systems (Rock Hill, SC), a company that is currently offering a sub $10K 3D printer. This disruptive technology has the potential to drastically change the landscape of the conventional manufacturing supply chain.

6 Potential health and occupational hazards

Conventional manufacturing processes such as casting, forging, and machining generate various air/water emission, noise, fluid spills, and wasted chip powders which are potential health and occupational hazards. The main heath risk generated by traditional manufacturing processes is oil

Table 3 Summary of reported energy consumption of different AM processes

Type of equipment	SLA			SLS					FDM			
Name of equipment	SLA250	SLA3500	SLA5000	Model2000	Model2500	Vanguard HiQ	HiQ + Hs	EOSINT P 390	1650	2000	8000	Quantum
Energy consumption rate (kWh/kg)	32.47	41.38	20.70	40.09	29.83	14.5	56.75	66.02	346.4	115.2	23.08	163.69

mist resulted from metalworking fluid. Long-term exposure to oil mist can lead to increased susceptibility to several types of cancer. Oil mist can also cause diseases such as oil acne, contact dermatitis, bronchitis, bronchial asthma, and lung fibrosis. Noise also presents a fairly common workplace hazard. Occupational hearing loss is the most common work-related injury in the USA, with 22 million workers exposed to hazardous noise levels at work and an estimated $242 million spent annually on worker's compensation for hearing loss disability [64, 65]. These problems can be avoided using AM processes. However, AM processes may create new health problems. Therefore, it is important to investigate the toxicological and environmental hazards that may occur due to handling, using, and the disposal of the materials used in various AM processes. These investigations can help achieve pollution prevention and reduction of occupational hazards and health risks. They may also prove to be a catalyst for greater acceptance of the AM industry.

A wide assortment of materials like epoxy resins, cyanoacrylates, polycarbonates, acrylates, elastomers, acrylonitrile/butadiene/styrenes, and nylons (polyamides) have been introduced for AM during the last two decades. However, the effects of some of the materials are not well understood. For example, a low-viscosity carbonate-epoxy-based liquid resin known as "TuxedoTMG3-HCM" was introduced by American Dye Source over 10 years ago [66]. Some experiments carried out on laboratory animals showed that TuxedoTMG3-HCM could cause genetic alteration and mutation, and change cell structure. However, its potential health effects have not been tested, and no limit has been laid on how much a human being can be exposed to this chemical [66].

Various studies on AM materials concluded that harsh skin reactions and eye irritation and allergies can occur when the operator comes in contact with these chemicals by either inhaling the vapors or if the materials accidently spill on the skin. Prolonged exposure to these chemicals may lead to chronic allergies though nothing can be said about whether they can be fatal. Since the majority of the chemicals are long-chain molecules, their biodegradability is very poor and the materials remain in the environment for extended periods of time. Poisonous gases like carbon dioxide (CO_2), carbon monoxide (CO), and nitrogen oxides are found to be emanated after the breakdown of these chemicals. It has also been predicted that noxious halocarbons (CFCs, HCFCs, CCl_4), trichloroethane (CH_3CCl_3), nickel, and lead compounds might emerge from the operations of AM machines. Therefore, the environmental impact of the AM industry is a subject of great concern [48].

Even though some researchers [48] have acknowledged the need for standardization of raw materials in the AM industry, the potential toxicity, environmental hazards, and chemical degradability of solvents used for their removal still remains a topic of considerable research potential.

Along with the few harmful after-effects of photopolymer liquid resin, not much is known about the effects of the solvents (propylene carbonate, tripropylene glycol monomethylether, isopropanol) used to dissolve support structures left after making prototypes in SLA. Nonetheless, they are known to cause some symptoms like skin burns and respiratory uneasiness. Table 4 showed different chemicals used in various AM processes and their occupational and environmental effects [67–74]. It can be observed that most of the chemicals are not really harmful to humans except one or two like photopolymers and propylene glycol. Nonetheless, AM machine operators need to be educated in handling and disposal of these materials along with the handling of high-intensity laser beams. Safety equipment like masks, goggles, and working gloves must obviously be provided in the work area. Slowly and steadily, AM processes will surely become safer and safer for the operators as new technological and safety features are developed and implemented in AM machines.

7 Conclusion

After 30 years of research and development, AM has evolved from a niche process for rapid prototyping to a legitimate manufacturing process for parts production. Many companies are producing commercial parts using AM process. For example, Boeing now has 200 different AM part numbers on 10 production platform [75]. Several mainstream publications, including the *Economist*, *Forbes*, and *USA Today*, have brought public attention to the AM technology. The April 2012 issue of the *Economist* billed AM as the production technology of the future and called it "the third industrial revolution." It is highly likely that AM will have a significant societal impact in the near future. A critical technical review of the promises and potential issues of AM is beneficial for further advancing its development.

This review identified many positive impacts of AM, summarized as follows:

- *Customized healthcare products to improve population health and quality of life*. AM has been used to produce customized surgical implants and assistive devices in the healthcare industry. Researchers are now investigating the use of AM to produce scaffolds for tissue engineering applications and drug delivery devices. Because AM is well suited to produce customized products, it is expected to play a significant role in personalized healthcare to improve the safety, quality, and effectiveness of healthcare for the general population.
- *Reduced environmental impact for manufacturing sustainability*. Compared to conventional machining processes, AM is more efficient in terms of virginal material consumption and water usage. It does not require the use of coolant and other auxiliary process inputs, and thus produces less pollution to the terrestrial, aquatic, and

Table 4 Occupational and environmental effects of different chemicals used in AM processes

AM process	Chemical/solvent	Emissions	Hazards of usage	Biodegradability
SLA	Propylene carbonate	CO_2,CO,SO_x	Low system toxicity was found in rats	Readily biodegradable (more than 80 % degraded in 10 days)
	Urethane resins		Too much ingestion may lead to vomiting	Not found to be dangerous to the environment
	Tripropylene glycol		Slight irritation after eye contact. No absorption or irritation to the skin.	Can be biodegraded by 50 % in just 8.7 days, and by 81.9 % over a 28-day test period
	Isopropanol		Irritation and burning sensation in eyes and sometimes corneal injuries; irritation and soreness on the skin and prolonged exposure may cause dermatitis	Has a potential to acutely decrease oxygen from aqueous systems
SLS	Polyamide resin	CO_2	No serious hazards were found during handling or exposure to this chemical	Form inflammable mixture with some chemicals or long exposure to air
	Acrylonitrile butadiene styrene		Molten plastic likely to cause lethal burns, processing fumes may lead to eye irritation and choking of the respiratory tract	Since it is insoluble in water, its eco-toxicity is low
LENS	Photopolymers	CO_2,CO,SO_x	Inhalation may cause ulceras and burning in throat and coughing; contact with skin and eyes causes redness, irritation and swelling	No hazardous decomposition products
FDM	Propylene glycol monomethylether	CO_2,CO,SO_x,PM^c,NO_x	Irritation in eyes, skin, nose, throat; headache, nausea, dizziness, drowsiness, incoordination; vomiting, diarrhea	No hazardous decomposition products

atmospheric systems. It also requires less landfill. Therefore, AM is expected to become a key manufacturing technology in the sustainable society of the future.

- *Simplified supply chain to increase efficiency and responsiveness in demand fulfillment*. AM is conducive to innovative design and enables on-demand manufacturing. As a result, the need for warehousing, transportation, and packaging can be reduced significantly. With proper supply chain configuration, it is possible to improve cost efficiency while maintaining customer responsiveness using AM. With the advent of personal AM machine, the dream may come true where customers can obtain desirable products economically whenever they want and without leaving their home.

This review also identified two areas that need further research attention. First, more research is needed to accurately evaluate the energy consumption of various AM processes. A standardized procedure should be developed that takes into account various aspects of operating an AM machine. It is possible that when producing the same part, AM consumes more energy than conventional manufacturing processes. However, AM allows design optimization that can lead to products with the same functionality but having less weight compare to that to be produced using conventional manufacturing processes. Taking into account supply chain simplification, the life-cycle energy consumption of such optimized and on-demand produced parts is likely to be comparable, if not less than that of traditional parts. Granted, the evaluation of life-cycle energy consumption of a product is a complex task. Further research advance in LCA may shed more lights on how to assess the energy efficiency of AM. Second, there is a need to better understand the potential occupation hazard of AM. The health effects of various AM materials have not been well established. As the AM industry continues to evolve and expand, there is no doubt that government regulation will be needed to safeguard the AM workforce. Research in this area will help provide guidelines for such regulations. It will also enable the development of safe AM machines that can be used in a home environment.

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