EXPLORING ADDITIVE MANUFACTURING AND ITS POTENTIAL IMPACT ON FREIGHT TRANSPORTATION

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Introduction

The additive manufacturing (AM) industry has grown extensively since the 1980s, transforming from a niche technology accessible only to field experts to a publicly-accessible global phenomenon that is spawning international communities, companies, and markets. AM proponents speculate that it will significantly disrupt conventional manufacturing and transportation systems while skeptics argue that it will remain a fringe technology with only marginal impacts.

This paper examines the current state and future capabilities of additive manufacturing, identifies industries as candidates to adopt AM, and discusses the potential impacts AM could have on the freight transportation system. It is intended to increase the exposure of AM to the transportation community and encourage more research into its potential effects on the transportation system. Although this paper postulates certain scenarios to present a range of plausible AM outcomes, these scenarios are largely conjecture-based and highlight the need for more research and understanding of this topic.

Background

Additive manufacturing, also known as 3D printing, encompasses several technologies that can be used to manufacture 3D objects from 3D computer models. AM constructs objects layer by layer. This is different from popular manufacturing techniques such as subtractive manufacturing which removes material from a block or injection moulding which uses dies and casts to shape objects. Although individual AM technologies are quite different, they all follow three basic steps [1], with some requiring an additional fourth step [2]:

The first step is 3D modelling and design which can be performed using professional- or amateur-oriented commercial-off-the-shelf software (shown in Figure 1) [3]. Alternatively, designers can scan objects and generate a 3D rendering that can be imported into 3D modelling software. Technological advancements are expected to reduce the 3D printing learning curve to a level comparable to 2D printing, whereby creating and printing a 3D design is as simple as creating and printing a document [4].

Figure 1: 3D modeling [2]

Figure 2: 3D model layers [5]

The second step is pre-processing (conceptually shown in Figure 2). This converts the 3D model file into a 3D printer file. A quality check is performed during this conversion to ensure that the design is physically feasible.

The third step sends the printer file to the 3D printer for fabrication.

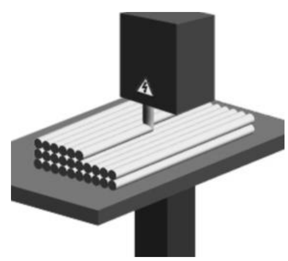

Figure 3: 3D print tool paths [6]

Objects are fabricated layer by layer by a printer “head” that follows a predetermined path defined during pre-processing (shown in Figure 3 and 4). Once one layer has been completed, the build platform is lowered by the layer thickness and the next layer is formed directly on top of the previous layer. AM fabrication methods can utilize various materials, from ceramics to chocolate; however, plastics and metals are the most common [7]. Raw material costs range from $5-20 per kg for plastics [8] to $200-400 per kg for metals [9].

Some types of AM require a fourth post-processing step. This includes cleaning, extra curing or hardening, removing support structures, removing extra or excess material, or surface finishing.

Figure 4: Additive manufacturing layer by layer fabrication process [6]

Modern AM technologies originated in the 1980's and have made significant advancements since then. Table 1 provides an abbreviated history of AM and highlights some key milestones.

Table 1: Additive Manufacturing Timeline

Year	Event
1984	First 3D printer is invented [10].
1988	First fused deposition modelling (FDM) machine is invented and costs approximately $130,000 [11] .
1996	Term "3D printer" is first used to describe rapid prototyping machines [11].
1999	3D printed urinary bladder is implanted into a human [10].
2005	3D printer is created that can print most of its own parts [10].
2006	First 3D printer using multiple materials at one time [11].
	Contour Crafting, a technology that can "print" a house, is invented [12].
2008	Thingiverse, a 3D model sharing website, is launched [13].
2009	First blood vessel is printed using a "3D bioprinter" [10].
2010	First car made primarily of 3D printed parts is constructed [14].
2011	First 3D printer capable of printing with chocolate [15].
2012	3D printed prosthetic jaw is implanted into a human [10].
	First consumer grade 3D printer that costs less than $500 [16].
	GE announces supply of 25,000 3D-printed jet engine nozzles per year to aircraft manufacturer starting in early 2016 [4].
2013	Functional 3D-printed gun is made; design is made public [17].

3D printing is becoming a mainstream technology through 3D printing communities and online marketplaces which offer resources for creating and downloading 3D designs. Thousands of 3D models can be purchased online and printed from home. The cost of high quality 3D printers has introduced opportunities for businesses to provide 3D printing services. These businesses allow consumers to select a product they want 3D printed or upload their own 3D file. Finished products can be picked up or delivered to the customer's home in less than a week.

Strengths of Additive Manufacturing

Additive manufacturing has several strengths compared to traditional manufacturing such as high material efficiency, improved design flexibility, and increased production flexibility [1]. These strengths allow AM to respond to niche markets; however, before disrupting the transportation system this technology must overcome several critical weaknesses listed in the next section.

Material efficiency refers to the proportion of raw material used in the final product, as well as the proportion of raw material that contributes to the functionality of the product. This characteristic varies widely between different additive manufacturing technologies. [1]. AM has improved material efficiency over traditional manufacturing by requiring less material input and producing less waste material, reusing leftover raw material, and optimizing material usage at the design stage. Since AM builds objects layer by layer, virtually all input material forms part of the finished product. Furthermore, the little waste that is produced "can often be reused with minimum processing" [1]. AM can also achieve higher material efficiencies at the design phase. Figure 5 shows a traditionally manufactured airplane seatbelt buckle and a 3D printed buckle. Both meet the same structural requirements but the 3D printed buckle is lighter and uses significantly less material. Extending these design practices to large scale manufacturing processes can significantly reduce raw material requirements and result in lighter products – both of which have impacts on truck volumes and weight characteristics.

Figure 5: Current airplane seatbelt buckle vs. 3D printed buckle [18]

An important strength of AM over traditional manufacturing is the ability to cost-effectively customize parts. Referred to as “mass-customization,” AM can produce highly complex parts in a single process, reduce the risk of design changes, and create opportunities for manufacturing new products that cannot be made otherwise [19]. In traditional manufacturing processes design changes can be quite costly and require new equipment or moulds. Conversely, one 3D printer can be used to produce a countless number of designs. Additionally, mass-customization allows manufacturers to adapt quickly to changing markets because it is economically feasible to produce low volume batches of any product [19].

Production flexibility refers to the freedom of manufacturers to locate their production sites. AM improves this by allowing manufacturers to locate closer to their consumer market. This could encourage overseas manufacturers to relocate closer to domestic consumers to save time and resources associated with transportation [20]. Locating production sites closer to consumers can also reduce inventory costs. Observations of existing businesses models have proven that AM can be used to manufacture products on demand. This could eliminate large storage areas for inventory or even retail centres entirely.

Weaknesses of Additive Manufacturing

Although breakthroughs in AM are occurring regularly there are many limiting factors of this technology including the size and structure of objects that can be 3D printed, material availability, and structural stability of intricate designs.

The size of a 3D printed object is limited by its structural stability and the 3D printer. The width limits of the object are constrained by the reach of the print head while the height limits are constrained by the vertical range of the platform. Some industrial grade 3D printers can create parts as large as $2.25m^3$ [18], while consumer grade 3D printers “often have print beds smaller than one cubic foot” [21]. Larger 3D printers may not yield larger products since the size of 3D printed objects is also limited by the structural properties of the printing material and the stability of the design. In most types of additive manufacturing, the raw materials are placed onto the platform in a molten state and are prone to deformation during the production process. Additionally, objects can deform under their own weight when they get too large. Disposable supports can be used to provide temporary structural support during production. Large objects can also be printed as a series of smaller parts and then assembled, although this defeats some of the purpose of AM.

In general 3D printers are available as consumer grade or industrial grade. Consumer grade printers produce low quality objects and are typically limited to producing plastic toys and models. Industrial grade printers produce high quality objects and are typically used for prototyping or direct part manufacturing. Currently consumer grade printers can cost less than $500 [22], whereas industrial grade printers can cost upwards of hundreds of thousands of dollars [19]. More expensive 3D printers do not guarantee shorter build times [6].

In 2010 about 50 different materials [23] ranging from plastics, metals, ceramics, paper, waxes, sands, and even edible products (e.g. chocolate) were available for 3D printing. Not all 3D printers are capable of using each material. Most consumer grade 3D printers can only print with one or two materials [6] while some industrial 3D printers can use multiple materials in the same print.

AM processes are currently unable to match the accuracy and surface finish of traditional manufacturing processes [24]; therefore 3D printed objects commonly undergo post-production processing which can be costly and time consuming. Technological advancements continue to bridge the gap between AM and traditional manufacturing. For instance, some higher performing 3D printers can rival injection moulding technologies by achieving tolerances of 0.02 mm [2], although most 3D printers use a layer thickness between 0.2 and 0.3 mm [25].

The current production speed, or lack thereof, and cost of 3D printers are AM's biggest weakness in terms of being a viable alternative to traditional manufacturing technologies. This weakness is being addressed through continual technological advances that are increasing production speed and reducing printer costs. For example, prototypes that once took days to manufacture with traditional manufacturing methods can now be completed in just hours with 3D printers [26]. Despite these advancements traditional manufacturing methods are still favoured for mass manufacturing.

Manufacturing processes can be split into the design phase and the production phase. Generally AM processes are faster and cheaper during the design phase since AM does not require the time and cost required to develop the moulds and customized machinery of traditional manufacturing [19]. Conversely, traditional methods are generally faster and cheaper during the production phase [27]. Research has shown that the production costs and volume of AM and injection moulding are similar when between 50 and 50,000 product units are manufactured [19]. AM is more appropriate for manufacturing fewer than 50 units and injection moulding is more appropriate for manufacturing more than 50,000 units. This finding is highly dependent on specific manufacturing technologies and the type of "units" being manufactured.

There are instances when AM is more cost and time efficient than traditional methods regardless of production volume, such as manufacturing highly complex products. An example of this is General Electric's (GE) plan to supply 25,000 3D printed jet engine nozzles per year to a major aviation company starting in 2016 [4]. A driving factor for GE to use 3D printing was the ability to manufacture nozzles as a single unit rather than welding together 20 small individual components [27].

Before AM can become a viable option for the manufacturing industry, 3D printers must continue to increase their production speed. Current printers can take days to print large objects and hours to print smaller ones "compared to traditional means of manufacturing that crank out products by the minute" [21]. The production speed gap could soon be significantly bridged as the U.S. Department of Energy's Oak Ridge National Laboratory (ORNL) is looking into an additive manufacturing process that would be 200 – 500 times faster than current methods [21].

Although AM technologies have been available for several decades, they have not yet been widely adopted by industry. According to some industry analysts, widespread adoption of AM may only occur in about 10 years [28]. There are many possible reasons for the slow adoption of additive manufacturing, including lack of knowledge about AM processes, lack of testing of materials and final products, and the lack of incentive to switch from traditional manufacturing methods. Extensive testing, demonstration, and data collection related to AM is necessary before AM can have a major impact on the manufacturing industry and on transportation networks [29].

Candidate Industries for Near-Term Adoption of AM

Certain industries are adopting AM and others are candidates for using AM in the next few years. In general the industries that have been most impacted by additive manufacturing are ones that benefit from mass customization or want to produce highly complex objects. These industries include, but are not limited to, prototyping/modeling, medical/dental, art and fashion, and aerospace/automotive.

Many companies use 3D printers for models or prototypes because "3D printing enables the designer to produce multiple iterations of a design in the same amount of time it would take to produce only one model" [16] using other manufacturing methods. Similarly, AM processes can be used to create cost effective visual aids [16].

3D printers used in tandem with 3D scanning technologies are enabling medical professionals to create custom medical devices, such as hearing aids and dental ware. AM processes are also opening up "bio-printing" opportunities, allowing doctors to manufacture human organs and tissues in new and innovative ways [30]

3D printers are attracting interest from the art and fashion industries due to the ability to create unique shapes and objects that were previously difficult or impossible to manufacture [31]. Additive manufacturing is being used to create a wide range of products from customized jewelry to designer furniture. Some designers have even used AM to create clothing.

The aerospace and automotive industries have been early adopters of AM, especially concerning spare parts [1]. Aerospace industries often require spare parts without warning. Companies that rely on traditional manufacturing processes are required to keep thousands of rarely used parts in storage. Companies that use AM would only need to have a 3D printer, raw materials, and the 3D design files for their parts on hand to meet their spare part demand. This type of scenario applies to other similar industries which require parts for older vehicles models, such as the automotive industry.

Another area of the aerospace and automotive industries that has the potential to see major changes due to AM is in the design and manufacturing of new parts. AM processes facilitate the design and construction of more complex and innovative shapes and parts that use material more efficiently. This is evidenced by the introduction of designs and products that were not economically feasible or physically possible using current manufacturing processes [17].

Potential Impacts of Additive Manufacturing on Freight Transportation

To date AM has only impacted a few industries and has had little impact on the freight transportation system. The acceleration of technological advancements in 3D printing since the 1980s suggests that it is only a matter of time before AM becomes mainstream. The challenges that AM must overcome suggest that it could be years before AM starts altering freight transportation systems or it could be decades. Given the plausibility of AM to significantly change goods movement patterns, it is worthwhile to ask hypothetical questions about the potential impact of this technology for the purpose of testing theories, encouraging research, and perhaps preparing for these impacts.

Could the widespread adoption of AM create a shift from global supply chains to localized distribution? Many manufacturers rely on integrated and often global supply chains. Raw material is sourced from various locales, value-added processes are performed at different locations, and just-in-time delivery systems ensure that individual components arrive at specific locations and times. This process often involves long distance movements subject to high costs, long travel times and high variability, and compliance with complicated international tariff and trade laws.

Once, and if, AM production speeds compete with current mass manufacturing methods, global supply chains could be replaced by small, agile, and independent manufacturers that are better positioned to respond to fluctuating inventories and market demands [32]. Global supply chains requiring an integrated intermodal network of ships, trains, and trucks could be replaced by local goods movement systems consisting primarily of short trips performed by small delivery trucks. This could introduce significant shifts in the spatial, temporal, and physical characteristics of the transportation system, altering trade routes and patterns, changing product delivery expectations, and utilizing modes differently.

Could AM reduce freight demand? In addition to reducing the length of freight-related trips, additive manufacturing has the potential to reduce the number of freight-related trips. There are two primary ways in which this could happen: (1) increased material efficiency; and (2) increased supply chain efficiency. According to some researchers, it is not uncommon for 95% of raw material used in manufacturing aerospace parts to end up as waste [33]. On the other hand, additive manufacturing processes are notoriously material efficient, and waste material can often be reused. Therefore, if additive manufacturing replaced traditional manufacturing processes increased material efficiency would mean that less raw input material and less output waste material would need to be transported to manufacture the same number of products. With that said, some researchers believe that the speed, convenience, and price of additive manufactured products could lead to a drastic increase in the number of products being manufactured [34]. Therefore, it is uncertain whether there would be an increase or decrease in freight trips related to the transportation of raw materials.

AM processes also have the ability to reduce the number by altering the supply chain. Since 3D printers go directly from raw materials to finished products there would be a significant decrease in the number of trips related to the transportation of semi-finished products [35]. Additionally, since products would only be manufactured in response to consumer demand, there would be also be a reduction in total trips related to the transportation of stock that eventually goes unsold.

Could 3D printing change consumer behaviour and travel patterns? Research conducted in 2013 compared the cost of purchasing 20 common household items (e.g., smartphone case, garlic press, showerhead) online to 3D-printing them using free designs from online marketplaces. The purchasing cost (excluding shipping) was between $312 and $1,944. The 3D printing cost (excluding the printer cost) was $18 [36]. This demonstrates the feasibility of household 3D printers to eliminate certain trips to local retailers.

Could the widespread adoption of AM lead to major transportation mode shifts? 3D printers require raw material such as plastics, powders, and metals. These materials are dense, time insensitive, often sourced from remote locations, and attractive for rail transport. Therefore AM could initiate mode shifts in goods movements where raw materials are transported along rail networks to urban centres and then to individual local manufacturers and retailers. This differs from current systems that also commonly use rail to transport raw material to large manufacturing plants but then usually use trucks to perform intermediate movements between manufacturing plants, distribution centres, and retailers. AM could result in some medium and long haul truck movements of finished and semi-finished goods being replaced by rail movements of raw material.

What if AM does not replace traditional manufacturing? There is a tendency to view AM and traditional manufacturing as opposing methods. This is not necessarily true. Perhaps the most plausible future is where AM and traditional manufacturing are complementary methods [37] where AM is used to improve current manufacturing methods, with minor impacts on production sites and supply chains [27]. AM could also remain a manufacturing method for niche and specialty markets. Much of the speculation surrounding AM technologies are reliant on the realization of technological improvements that are not currently feasible [4].

Conclusion

Advancements in computer programs, machinery, and materials have opened up opportunities to transform AM into a mainstream manufacturing option. Compared to current manufacturing systems (e.g., injection molding), 3D printers can improve material efficiency, are effective at manufacturing customized products, and provide the flexibility of manufacturing products wherever a 3D printer can be set up. However, they are currently unable to match the mass production capabilities of current systems. Even with recent technological advances, further development, research, and testing is required before AM can become widely adopted. Most experts agree that it is only a matter of time until AM becomes a regular occurrence in the manufacturing industry, as a stand-alone process or combined with traditional manufacturing methods. The potential of AM to alter supply chains could shrink global trade patterns to the local level. However, significantly more research is required to appropriately assess the potential impacts of additive manufacturing on freight transportation systems.

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