Modern Additive Manufacturing Technologies: An Up-to-Date Synthesis and Impact on Supply Chain Design

Michail Thymianidis¹, Charisios Achillas², Dimitrios Tzetzis³, Eleftherios Iakovou⁴

¹School of Economics and Business Administration, International Hellenic University, Thermi, Greece
²School of Economics and Business Administration, International Hellenic University, Thermi, Greece
³School of Economics and Business Administration, International Hellenic University, Thermi, Greece
⁴Department of Mechanical Engineering, Aristotle University of Thessaloniki, Greece
¹m.thymianidis@ihu.edu.gr, ²c.achillas@ihu.edu.gr, ³d.tzetzis@ihu.edu.gr, ⁴eiakovou@auth.gr

Abstract

In the last fifteen years the mass production of the modern industry has been shifted to third world countries, especially Asia. European firms are faced with the need to promptly adjust towards the fabrication of low volume custom-made products with high added value by developing new advanced manufacturing technologies. Additive manufacturing (AM) is an advanced technology that could enhance manufacturing. In particular, with the use of AM technology products are manufactured by building up thin layers of materials from digitized three-dimensional (3D) designs virtually constructed using advanced 3D Computer-Aided Design software. This free form fabrication enhances the design potential, allowing end-products to comply with functionality thus pushing the boundaries of manufacturability. The impact of AM technologies on supply chains could be massive since shrinkage of the product development cycles and development costs can be achieved along with rapid innovation cycles. Additionally, novel product concepts can be pursued since cost and time to prototype and manufacture are diminished. The potential is almost endless, making tremendously flexible the small-batch manufacture firms in the event they pursue domestic advanced manufacturing. The aim of this paper is firstly provide a state of the art synthesis of AM technology, their limitations, their adoption rate by various industrial sectors and secondly to outline their emerging impact on supply chain design and management.

Keywords: Additive manufacturing, 3D printing, restructured supply chains, case studies.

1. Introduction

Additive Manufacturing (AM) technology, which is often referred to as three dimensional printing surfaced in the late 1980’s with sales beginning to increase at a faster rate in early 1990’s (Kruth et al., 2007). It took almost two decades of research before AM finally seems to be capable to become a
disruptive technology regarding traditional supply chains and their way of manufacturing which mostly relies on subtractive processes, such as CNC machining and formative processes like casting or molding (Reeves, 2009). Three dimensional printing technology instead produces objects layer-by-layer (additively), rather than subtracting similar to a two dimensional printer with the only difference that a third dimension (z-axis) is added, which is also called the building direction (Reeves, 2009).

It is necessary to distinguish between two major additive manufacturing categories in order to establish that AM encompasses different manufacturing procedures. Historically, AM technology was used to build conceptual prototypes referring to that process as Rapid Prototyping (RP), a term which is still often used as a synonym to AM. Those prototypes were meant only to accelerate the development phase (time-to-market) of a product and under no circumstance are comparable to the end product regarding quality, material and durability (Fenstra, 2002). Scientific research was an important driver for RP technology development which boosted printer capabilities towards manufacturing functional prototypes leading inevitably to Rapid Manufacturing (RM). Rapid Manufacturing has evolved through RP due to technological advancements defined by Rudgley (2001) as “the manufacture of end-use products using additive manufacturing techniques (solid imaging)”. Given the scientific and technological advancements in the field of AM in the past decade, this work distinguishes RM from RP due to the use of advanced printing techniques enabled by a range of sophisticated materials which facilitates manufacturing products with long term consistency for the entire product life cycle (Levy et al. 2003). According to Wohlers Report (2011), RM was responsible for approximately 20% of overall AM revenues in 2010.

Rapid Tooling (RT) is considered a sub-category of RM; it aims only to create consistent tools which serve traditional manufacturing procedures (Dimov, 2001). RT has been mostly used to create injection molds but recent developments now enable RT technology to be used for casting, forging and other tooling processes (Levy et al., 2003). Kruth and Schueren (1997) partitioned RT further into direct tooling in which moulds are layer-manufactured for use, and indirect tooling where a master model is created and furthermore used to produce a casted mould for example. According to Wohlers Report (2009), 16% of AM processes were used for direct part production (RM), 21% for functional prototypes (RP) and 23% for tooling and metal casting patterns (RT) from which approximately 56% and 9% of process preferences were direct metal and direct polymer tooling respectively (Levy et al., 2003).

The AM process begins with a three dimensional representation of the object to be printed. Object representation is stored in a STL file (stereolithography), generated by conventional CAD software or obtained from laser scanning, Computer Tomography (CT), Magnetic Resonance Imaging and mathematical modeling software (Reeves, 2009). Afterwards, the STL file is imported into slicing software in which the three dimensional digital object is sliced into layers and oriented appropriately in order to define the best possible tool path for the printer which then creates the object via selective placement of material (Campbell et al., 2011). Furthermore, it is essential to choose the appropriate building direction as it can change specifications of the object such as quality, cost and lead time. Choosing a
direction other than the optimum would lead to more layers required resulting in increased lead time needed to manufacture the product (Reeves, 2009).

This paper aims to provide a comprehensive review of literature, technologies and manufacturing practices on modern Additive Manufacturing. The main focus is on Rapid Manufacturing and its subcategory Rapid Tooling which advanced in the past decade and now seems ready to significantly impact contemporary complex supply chains. The rest of the paper is organized as follows. In section two the most widely applied and advanced technological processes of AM are presented. This section is also complemented with the technological limitations and design restrictions AM is currently facing. Section three focuses on the adoption of AM by various industries. Finally, in section four the possible outcome and the impact of AM technology adoption are discussed towards the identification of the radical changes along modern supply chains that a full scale adoption of RM is expected to introduce.

2. Additive Manufacturing Technological Processes

Given the great amount of scientific research and the technological developments which introduced a wide scale of different mechanisms and materials, AM processes can be categorized in many ways. Firstly, as depicted in Fig. 1, AM processes use four large material categories, namely polymers, metal, ceramic and composite materials (Levy et al., 2003). Furthermore, it is quite obvious that RM uses all four material categories given that there is a wide range of products produced with different materials, while RT uses only polymers and metal for tooling applications.

Figure 1. Modified diagram of material dependent AM

Another categorization of AM processes can be based on grouping the processes according to material state and form as shown in Table 1 (Kruth,
Kruth (2007) identifies three basic types of bulk material used, namely liquid, powder and solid layers. Liquid material is used at processes like Stereolithography (SL), Fused Deposition Modeling (FDM) and Ink Jet Printing (IJP), whereas powder is used for Three Dimensional Printing (3DP), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM) and Direct Metal Deposition (DMD). Lastly, Laminated Object Manufacturing (LOM) can use solid layers of any of the four material categories to create an object.

<table>
<thead>
<tr>
<th>Material Form/State</th>
<th>Process</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid</td>
<td>SL</td>
<td>Polymers</td>
</tr>
<tr>
<td></td>
<td>FDM</td>
<td>Polymers</td>
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<tr>
<td></td>
<td>IJP</td>
<td>Polymers</td>
</tr>
<tr>
<td>Powder</td>
<td>3DP</td>
<td>Polymers, Metals and Ceramics</td>
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<td></td>
<td>SLS</td>
<td>Polymers, Metals and Ceramics</td>
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<td></td>
<td>SLM</td>
<td>Polymers, Metals and Ceramics</td>
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<td></td>
<td>EBM</td>
<td>Metals</td>
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<td></td>
<td>DMD</td>
<td>Metals</td>
</tr>
<tr>
<td>Solid</td>
<td>LOM</td>
<td>Polymers, Metals, Ceramics and composites</td>
</tr>
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</table>

Source: Kruth, 2007

2.1 Stereolithography (SL)

Stereolithography (SL) is the first commercialized AM technology using laser technology to achieve the photo-polymerization of liquid resin which becomes consistent when exposed to the laser (UV light) in order to create plastic objects (Fig. 2). After each layer is completed the platform lowers itself by one layer usually allowing the blade to replenish the liquid resin on the surface of the object (xpress3d, 2012). This technology is still used for RP to create functional or conceptual polymeric products and for indirect RT to create master patterns for molding and casting processes. Generally, the layer thickness achieved depends on the model of the machine and ranges between 0.05 mm and 0.15 mm with a roughness of approximately 35-40 μm RA (Reeves, 2009). The main advantages of SL are the possible achievement of temperature resistance and the creation of complex structures with very thin walls. The main limitation of SL is the needed support structure to fabricate objects which consumes additional material and extends production time (Petrovic et al., 2011).

Figure 2. Stereolithography process
2.2 Fused Deposition Modeling (FDM)

Fused Deposition Modeling (FDM) is similarly to SL one of the most widely used processes in order to fabricate functional polymer prototypes (RP). However, polymeric material with equal properties compared to other thermoplastic materials is stored in solid state on a plastic thread spool until it reaches the liquifier positioned before the extrusion nozzle. Then, it is deposited through the nozzle in liquid form due to temperatures above melting point creating the new layer reaching again solid state by natural cooling (Fig. 3). Another thread spool serves to provide material (most times wax) in order to create support structures whenever needed (www.custompartnet.com).

Further developments in the last years increased building speed up to 500% by facilitating a new patented high speed motion control system with two separate axes moving independently- one for the building material and one for the support structure (Christopherson, 1998). Most common materials used are polycarbonates (PC) and ABS, providing advantages such as fast printing of low cost parts, use of water dissolve support structures and coating capability to improve quality, whereas major disadvantages of this process are poor surface quality, grainy color and dimensional precision lacking significantly compared to modern additive technologies (Petrovic et al., 2011).

Figure 3. FDM process
2.3 Ink Jet Printing (IJP)

Ink Jet Printing (IJP) is another popular process used for RP mostly, based on the two dimensional printer technology storing liquid thermoplastic build and support material in headed reservoirs (Fig. 4). The materials flow towards the inkjet head in which piezoelectric nozzles deposit droplets on demand to create layers down to 19 μm (Gatto et al., 1998). Although, IJT offers accuracy and surface quality the slow build speed, the few material options and the fragile finished parts makes this technology almost solely suitable for prototyping and investment casting (Kruth, 2007).

Figure 4. IJT process
2.4 Three Dimensional Printing (3DP)

The Massachusetts Institute of Technology originally developed this technology and licensed it to six companies for commercialization purposes (Sachs et al., 1990). Similar to IJP, a multi nozzle inkjet printing head deposits on demand, a liquid adhesive that binds immediately with the metallic or ceramic powder positioned in the powder bed as exhibited in Fig.5 (Reeves, 2008c). Afterwards, the powder feed piston elevates itself in order for the leveling roller to create the next layer, repeating this procedure until the object is finished and ready for after production processes such as supporting powder removal and sealant infiltration for additional strength and surface quality. Materials are limited but are still cost effective compared to other processes facilitating the print of large and small parts up to 1 m × 0,5 m × 0,25 m with a density of 94%, 12,5 μm surface finish (Levy et al., 2003). Levy et al. (2003) also discuss that although 3DP can reach, compared to other processes, very fast building speeds, ranging between two and four layers per minute its accuracy, surface finish and strength makes it only appropriate for conceptual prototyping and RT (e.g. lost foam casting patterns).

Figure 5. 3DP process

2.5 Selective Laser Sintering (SLS)

The Selective Laser Sintering (SLS) manufacturing process shows similarities between 3DP and SL. The difference to 3DP and SL is that a laser is sintering the object successive layer by layer instead of an inkjet head. Moreover, no support structure is needed due to the powder bed respectively (Fig. 6). The greatest advantage of SLS is the ability to sinter a wide range of materials (polymers, metals, ceramics, foundry sand and others) which are used traditionally for different RT processes and for prototyping (Kruth et al., 2007). Polymers are still the most commonly used material, like polyamide which reaches mechanical properties equal to components manufactured by compression molding and it shows even better properties in the case that it is...
glass bead reinforced (Seitz, 1997). Indicatively, in the production of metallic parts, DTM has developed a tooling process which applies polymer coated steel powder in which the polymer melts and acts as a binder during sintering and afterwards burned off in order for the porous area to be infiltrated with density improving bronze or copper (McAlea, 1997).

**Figure 6.** SLS process

![SLS process](http://www.custompartnet.com)

**2.6 Selective Laser Melting (SLM)**

The Selective Laser Melting process is quite similar to SLS (Fig. 7). The main difference between the two technologies is that in SLM the high power laser beam (Nd:YAG) is capable of fully melting almost any powder material (metal, alloys, ceramics and polymers) without the use of binding polymer material and the necessary post treatment (bronze infiltration). This ensures higher resolution and almost full density compared to 70% in SLS. However, sometimes support structures are needed, especially when complex geometries are fabricated which require more overall material and post processing (Mumtaz and Hopkinson, 2009). Materials such as stainless steel, alloy steel, tool steel, aluminum, bronze, cobalt and titanium can be used in the SLM process. The variety of materials makes this process suitable for a wide range of industries such as tooling, medical implants and aerospace for high heat resistant parts (www.custompartnet.com).

**Figure 7.** SLM process

![SLM process](http://www.custompartnet.com)
2.7 Electron Beam Melting (EBM)

Electron Beam Melting is applied for prototyping complex geometry objects or for manufacturing end-use injection moulds or die casts. It is also appropriate for RM where high strength and temperature resistance is sought with excellent mechanic properties and faster production speed, up to five times compared to other processes (www.engineershandbook.com). It is patented only by ARCAM AB which is the only supplier of EBM devices. As shown in Fig. 8, EBM process includes a filament made of tungsten which emits electrons (electron gun) accelerated to half the speed of light through the anode, creating a high energy beam up to 3000 W and over 2500 °C (www.calraminc.com) which melts due to kinetic energy titanium or cobalt chromium metal powder precisely due to electromagnetic focusing coils (Petrovic et al., 2011).

The greatest advantage of this process is the vacuum chamber which facilitates an optimal fabrication environment for oxygen reactive materials used for medical implants, such as orthopedic implants in order to achieve effective osseointegration or in aerospace appliances in which material impurities due to oxygen are strictly prohibited for safety reasons (ARCAM, 2012; Sedaca, 2011). Other advantages that the technology offers are energy efficiency around seven kW of average power and the overall component quality achieved which is comparable to wrought titanium and better than cast titanium (www.engineershandbook.com)

Figure 8. EBM process
2.8 Direct Metal Deposition (DMD)

Direct Metal Deposition is one of the most advanced AM technologies which gain more and more popularity in the manufacturing industry due to its ability to produce fully dense metal components with complex geometries, in a compared to other processes short amount of time with excellent dimensional accuracy (Dutta et al., 2011). The technology and process were developed and commercialized jointly between the POM Group and the University of Michigan. DMD is facilitated by a robotic control (arm) equipped with a powerful CO$_2$ laser which is responsible for the coordination of the additive process by producing a melt pool from a small amount of metal powder injecting it through the nozzle in order to build thin successive layers (Fig. 9).

This process distinguishes itself compared to others as it can be applied through the whole range of AM and furthermore, is able to repair and rebuild worn and damaged components or apply wear and corrosion resistant coatings. One particular machine model (DMD IC106) manufactured by the POM Group (Fig. 10), operates inside an inert gas chamber in combination with a dual powder feeder in order to facilitate the processing of exotic metals and alloys or the synthesizing of new materials. Today, DMD is applied to repair worn molds and dies, to remanufacture and repair high-value, long lead time parts in the aerospace and defense industry, to rapidly produce highly functional metal prototypes and finally, to bypass time consuming welding for hard facing components (Dutta et al., 2011).

Figure 9. DMD process
2.9 Laminated Object Manufacturing (LOM)

The Laminated Object Manufacturing (LOM) process relies on a feed mechanism that supplies material in form of sheets over the platform where a heated roller bonds the sheet on top of the previous one (Fig. 11). Afterwards, the outline of the new layer is cut either through a laser, a knife or a hotwire, keeping the rest of the layer as support structure proceeding to the next layer by lowering the platform by one layer of material thickness. According to Levy et al. (2003) layers can be joined with several methods, such as diffusion welding to fabricate forming and injection tools, soldering to manufacture injection moulds, pressure dies and casting tools, laser beam welding for metal sheets, forming tools and core boxes, bonding by adhesives for non-
metals and forming tools and lastly mechanical joining with screws and anchors. Scientific progress facilitates the fabrication of a wide range of materials like paper, polymers, composites, ceramics and metals with fast production times. However, LOM is only used for RP and RT considering the lack of dimensional accuracy, especially in the z-axis compared to other processes (www.rpworld.net). In the past two decades, efforts were focused on the development of a non-planar LOM process. Kalmanovich (1996) aimed towards a curved layer process to improve strength and surface quality by applying reinforced fiber foils able to adapt the object’s shape and curvature. Klosterman et al. (1999) developed a curved layer LOM process machine for monolithic ceramics and ceramic matrix composites in order to manufacture curved objects with diminished stair step effect, increased build speed and less waste.

**Figure 11. LOM process**

![LOM process diagram](http://www.custompartnet.com)

Source: [http://www.custompartnet.com](http://www.custompartnet.com)

### 2.10 Technology Limitations and Design Restrictions

AM has made significant steps towards being a disruptive technology in the past decades, but is still in its infancy and moreover much additional scientific progress is yet required. The first two and most obvious technical challenges are that AM is, until now, still limited to manufacturing small quantities of small parts compared to traditional manufacturing processes (Campbell et al., 2011). Another, technical challenge for RM which mostly applies to laser sintering machines is the inherent lack of mechanical properties consistency regarding manufactured products influenced critically by temperature fluctuations (Excell and Nathan, 2010). Regarding this problem Bourell et al. (2009) suggest the usage of in situ sensors in order to enable early defect detection regarding temperature control leading to decreased manufacture times.
Furthermore, regarding materials, Campbell et al. (2011) point out that often additively manufactured components possess weaker mechanical properties across their building direction (z-axis) and although many materials from different material categories are available for additive technology, material properties on different processes are absent and moreover absent specifications that provide material property databases are slowing down the shift of AM industry towards manufacturing end products. In addition, further development of design tools and CAD software would help designers coping with the seemingly endless complex design possibilities that AM offers. Furthermore, engineers would appreciate artificial design optimization tools which are capable of optimizing shape and material properties in order to increase operations efficiency through weight minimization, material usage, etc. (Frazier, 2010).

Finally, it seems that academic research and corporate development are not yet aligned capitalizing on scientific research and testing on new or improved materials, which are significantly slowed down due to the closed architecture and the absence of reconfigurable modules of today’s AM machines (Scott et al., 2012).

3. Adoption of Additive Manufacturing by Industry

Various cost benefit analyses efforts have documented that AM is particular meaningful economically for low volume production. In particular, Hopkinson and Dickens (2003) compared different RM techniques against traditional injection molding in order to create a break even analysis, thus proving that AM seems appropriate for low volume production considering that production cost is constant, whereas the cost of a injection mold is amortized across the production volume. Furthermore, Ruffo et al. (2006) developed an expanded estimation model using the full costing system. In addition, the authors argued that the RM process curve has a deflection for low production volumes in the cost-volume diagram, due to necessary processes which demand a certain amount of time.

Although, most industries still use RP to fabricate functional and conceptual prototypes, modern AM machines are capable of more than that. Firstly, the advancing machines are welcomed in the tooling industry offering new solutions. For example, the Company Concept Laser, a German tool manufacturer developed the Laser Cussing technique which facilitates the integration of conformal heating and cooling channels in injection molding inserts in order to maximize thermal management, whereas traditional subtractive produced tools required drilled holes which often had to be placed at non-optimal locations (Reeves, 2008a).

An industry which made great strides in adopting RM is the aerospace industry as parts often have complex geometries with unique airflow and cooling requirements. According to Freedman (2012), more than twenty thousand (20,000) parts were additively manufactured by industry giant Boeing and are already flying in military and commercial airplanes. Moreover, RM aids the industry by enabling fast creation, cost and weight effectiveness given that most parts fabricated are categorized as low quantity-high value
(Thryft, 2011). Additionally, an airline could save more than 2.5 million dollars per year given the fact that AM achieved a 50%-80% weight reduction of metal brackets (up to thousand per aircraft) which are used to connect cabin structures (Wohlers, 2011). RM’s huge potential seems to drive also aircraft manufacturer Airbus to explore capabilities and financial viability of AM technologies in order to produce huge printers which would be able to manufacture future aircrafts with new synthetic materials (Olson, 2012).

Another industry which seemingly adopts RM fast is the medical industry in which products require a high grade of customization considering the anatomical needs of every individual patient. For example hearing aid shells need traditionally many steps by a technician to be manufactured with lead times quoted mostly at one week and a “first-fit” rate of 65%, whereas RM offers less manufacturing errors and a lead time of one day with a “first-fit” rate above 95% (Wong and Eyers, 2010). Additionally, RM is used to manufacture dental prosthetics such as crowns and bridges. Wohlers (2011) estimates that more than six thousands of those copings are produced only with laser sintering machines sold by the company EOS, and moreover that approximately four hundred copings can be produced in one day compared to the maximum of ten by a skilled technician. However, RM is not only restricted for the cranial area but further extends to manufacturing limbs such as prosthetic arms and legs. Considering that the Food and Drug Administration rated nylon eligible for medical use in this field the material is nowadays used to additively manufacture limbs with equal quality (strong and sterile) and even less weight compared to traditional ones (Thryft, 2011). In addition, the US’ based Therics is able to produce biocompatible bone scaffolds used to fill the gaps between realigned fractures with the only implication of non-customization ability (Reeves, 2008b).

The automotive industry and their suppliers in particular, exploit additive technologies such as FDM in order to manufacture small batches of small interior parts considering the reduction of assembly time and the comparably inexpensive machinery required (Wohlers, 2011). Moreover, extreme motor sports like formula race cars and motorcycles are starting to integrate additive fabricated parts and components in the daily racing routine. For example, Italian company CRP Technology developed gearbox covers, fuel system float chambers, water pumps and water manifolds for a 250cc world championship motorcycle (McMath, 2006).

Additive manufacturing is appearing more and more in other industries. For example the Netherlands based company FOC, develops digital furniture like lamp shades, chairs and other decorative items and fabricates the product after it was ordered online, using nylon powder as material for laser sintering (Reeves, 2009).

First steps are even made in rapid manufacturing textiles. Bingham et al. (2007) investigated the possibilities, design freedom and current limitations of CAD software in order to manufacture textiles additively and furthermore even printed the world’s first conformal garment. The research showed that in case that materials and technology continue to advance it would be entirely possible to print textile garments with even more sophisticated link structures (Bingham et al., 2007).
4. Impact of Additive Manufacturing on Supply Chain Design and Management

Rapid Manufacturing evolved as a modern Additive Manufacturing process through Rapid Prototyping. Although, both terms are still perceived as the same technology it is worth mentioning that RM seems to be capable to become a disruptive force driving modern supply chains to change dramatically. While additively manufactured conceptual or functional prototypes affects only the “time to market” period with operational cost benefits, faster market response and innovation cycles, RM could affect the whole spectrum of today’s supply chains and logistic networks. It would further require strategic business changes such as increased collaboration and relationship with machine vendors and material suppliers, as those will be a crucial part of the supply chain (Mellor et al., 2012).

Fisher (1997) devised a seminal framework for supply chain strategy, based upon the categorization of products as functional and innovative. The design of supply chains for functional products with relatively predictable demand should be based upon an efficient strategy whereas for innovative products should rely on responsiveness for those cases where product life cycles are short and variety high (Fisher, 1997). The evident trend towards faster order fulfillment, shorter Stock Keeping Unit (SKU) lead times through complex supply chains and the increasing need of customization led to Mass Customization (MC) strategy (Reeves, 2008c). MC seems to be the next step of responsiveness focusing on the customers' emerging need of customization. Pine (1993) states that MC is about “developing variety and customization through flexibility and quick responsiveness”. Moreover, the author proposed the adoption of MC strategy to be applied in heterogeneous markets with fragmented demand and short product life cycles. Furthermore, Tuck et al. (2008) argue that MC can be attained via modularization or postponement (Tuck et al., 2008).

Most often in the relevant literature, the term “agile supply chain” is used for chains with high product variety and low volume production that seems to match the capabilities of AM. Moreover, RM seems to be able to redefine agile supply chains as it is capable to overcome conventional issues such as temporarily loss or decrease of agility due to fluctuating supplier lead times (Christopher, 2011). Berman (2011) argues that as opposed to MC, RM seems beneficiary for small production batches given that it does not attain customization through modularization or postponement, but through layer manufacturing as the whole product is manufactured already customized for end-use. Furthermore, this results into a decreasing need of supply chain integration and fewer suppliers required considering that products are manufactured in-house (Berman, 2011). According to Cooke (2012) this requires the adoption of a more regionally organized supply chain network, a departure from the traditional offshoring practice. AM seems to enable efficient nearshoring, thus it can fundamentally affect Total Landed Cost through reduced emissions, safety stock and pipeline inventory. In this light, AM has a great impact on supply chain design (Chatzipanagioti et al., 2011). Moreover, it is worth mentioning that well diversified companies with large numbers of SKUs will probably rely on a hybrid manufacturing system. Based on Pareto’s 80-20 principle, a relatively small number of SKUs which are
produced in large quantities could still be manufactured in a mass production system, whereas large numbers of SKUs produced in small quantities could be additively manufactured, exploiting AM's capability of MC. This would result most probably in a decreased safety stock and would eventually save time, effort and financial resources considering necessary machine set-up time. Medium-to-high volume RM production could become more and more relevant considering that the relatively high operational costs most likely will decrease as AM technology matures.

With the ever more increased adoption of electronic web based retail transactions, retailers are expected to be substituted more often as tier one agents of the supply chain by end customers. Similarly, Reeves (2008c) reports that supply chains will shift from the production-distribution-retail model towards a model where retail takes place electronically, initiating manufacturing and final distribution to the end customer. This is expected to result that manufacturing companies would increase their financial resources in form of additional working capital with almost no up-front costs for tooling or production set up (Fig. 12).

Figure 12. Traditional vs. modern AM supply chain

\[\text{Traditional Supply Chain}\]
\[\text{AM Supply Chain}\]

In addition, overall transportation of goods would shift from long distance transport of finished products delivered to retailers to raw materials ordered from short approximate distances considering that production sites could be strategically scattered near customers in order to decrease lead time significantly (Cooke, 2012). Reeves (2008c) agrees with the latter suggesting that RM is providing the great advantage of manufacturing rapidly and cost efficient small batches of products with complex design geometries which has two advantages. First, no tooling costs are required which means that production does not need heavy capital investments in fixed assets supporting the aforementioned reduction of single source supply chain and logistics risk, thereby reducing tremendously inventory and logistics costs. Second, the ability to produce end-use products eliminates manufacturers’ need to produce separate parts which then are assembled and inspected for proper quality, thus erasing assembly and inspection costs.
A study of Reeves et al. (2008) focused not only on the financial benefits of AM, but also highlighted the drastic improvements in respect to the products carbon footprint. In this light, molding and casting requires often greater material wall thickness due to operational constraints. Increased geometrical complexity in RM facilitates optimal design leading to a decrease in material consumption up to 40%. This results also in weight reduction which heightens cost efficiency in every stage of a product’s life cycle. In addition, molding and casting consumes vast amounts of energy, particularly for phase changes of materials (solid to liquid and vice versa). Modern additive technology requires less energy, thus offering significant economic and environmental benefits.

In order to produce the end-use product, subtractive technology often produces large quantities of material waste which is often over 90%. Oppositely to subtractive machinery, modern additive manufacturing techniques such as powder bed and powder feed are 97% material efficient wasting only a small amount of raw material due to non-re-usable powder. The most cited example is the aerospace industry in which buy-to-fly ratios are approximately 20:1. This ratio indicates that in order to produce one kilogram of component twenty kilograms of material has to be ordered. The remaining nineteen kilograms are waste requiring reprocessing or recycling which lead to excessive energy and financial resource consumption (Reeves, 2008c). AM’s waste efficiency minimizes waste recycling and disposal plus water and fuel consumption, which indicates that additive processes are not only agile but also poses a basic characteristic of lean operations such as waste minimization (Reeves et al., 2008). Moreover, the fabrication of almost any geometry aids the optimal design of cooling channels, as aforementioned. This effect leads to an increase of product functionality combined with operational efficiency. For example optimized injection molds manufactured with RT processes proved to be more efficient due to heat resistance which results in more produced components per mould. Another merit of RM is that it does not need to apply harmful chemicals such as cutting fluids avoiding this way their required disposal. Last but not least, significant CO₂ emission reductions may be achieved by the reduced volumes of transported goods, since production is shifted from distant manufacturers (often based developing countries) to in-house production, in proximity of products’ end markets (Reeves, 2012).

7. Conclusions

Rapid Manufacturing emerged the past decade through more advanced processes and machinery, bypassing the constraint of manufacturing only prototypes. This emerging method of manufacturing additively rather than subtractive, seems to be capable to restructure modern supply chains regarding lead time, operations, logistics, capital investment and production location. Although, AM made significant progress in the past years, it is constrained by major limitations, which seem not to be insuperable obstacles given the fact that AM processes have not mature yet, and there is still much to research. Nevertheless, major multibillion dollar industries, such as the
aerospace and medical industry, have “discovered” the value of RM by investing heavily in the expansion of the technology. There are many cases where RM is already more suitable for relatively low production volume compared to traditional injection molding. It seems that once the major obstacle of low-to-medium production is eliminated and AM is capable for mass production, it is likely that global manufacturing will witness a new industrial revolution, which is expected to affect more and more industrial applications and global supply chains.

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