Additive Manufacturing – A supply chain wide response to economic uncertainty and environmental sustainability

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Abstract

In this paper the author will review some of the current commercial applications of Additive Layer Manufacturing (ALM) and the business benefits associated with technology adoption. The paper will review applications such as Rapid Tooling, where ALM processes are being used to make fully dense tool cavity inserts with highly efficient heating and cooling channels. This approach has been proven to have clear down-stream economic benefits within the supply chain, resulting in reduced cycle times, improved moulding quality and a lower carbon footprint.

The paper will also address how ALM is being used as a sustainable alternative to subtractive machining in the production of high buy-to-fly ratio parts, and how different Design-For-Manufacturing (DFM) rules associated with ALM, are being exploited to manufacture lighter weight, energy efficient products with less raw material.

The paper concludes with a look into the future, possibly into a 'tool-less' society, where consumer products are printed to order, using the consumers own design data as-and-when they are needed, using either a globally distributed just-in-time supply chain or inversely manufacture within the consumers own home.

Keywords: *Additive Layer Manufacturing, Rapid Manufacturing, Rapid Tooling, Sustainability, Carbon Footprint*

1. Introduction

1.1 Historical context

Until the late 1980's, the majority of manufacturing processes were classed as either subtractive such as machining, or formative such as casting or moulding. These two methods of production have literarily dominated manufacturing since the Stone Age. However, with the advent and growth of 3-Dimensional Computer Aided Design software (3D CAD) has come something of a silent industrial revolution, where products can now be manufactured particle-by-particle directly from computer data, without the need to jigs, fixtures or mould tools. This method of production we now call Additive Layer Manufacturing or ALM.

Since ALM was first commercialised in California USA in the early 1980's [1] the technology has matured at an almost exponential rate. Parts manufactured on early ALM machines were used for little more than 'engineering design insurance', to validate design data and to provide simple form and fit prototypes. Move on 25-years and ALM technologies are now used to manufacture fully dense medical implants in materials such as titanium, mass produced devices such as hearing aids by the million, and consumer goods such as light fittings, jewellery and furniture customised specifically to the tastes of individual consumers.

However, along this journey ALM has also provided significant opportunities for companies engaged in both traditional tool making and production engineering.

1.2 Technology explanation

All ALM technologies follow the same core operating principles [2]. The ALM process starts with the enabling 3D computer representation of the objet to be built. This data can be generated using CAD software, or it can be obtained from none contact laser scanning, Computer Tomography (CT), Magnetic Resonance Imaging (MRI) or through mathematical modelling software. The 3D data is then translate into the STL surface mesh format, which has become the defacto standard within the ALM industry. Once the STL file is imported into the proprietary software used to control the ALM process, it is translated into the most suitable build orientation. Build orientation has a number of effects on the quality, cost and delivery of ALM parts. Firstly, because of the layer wise method of manufacture, low angled surfaces can have a relatively high surface roughness, when compared to other manufacturing processes. This roughness is caused by stair stepping [3], which can be detrimental to part quality. Figure 1 shows an electron microscope image of a typical low angled 10-degree surface produced using the Stereolithography ALM process. The thickness of each layer is 0.15mm. The resulting surface roughness is some 35-40 µm RA.

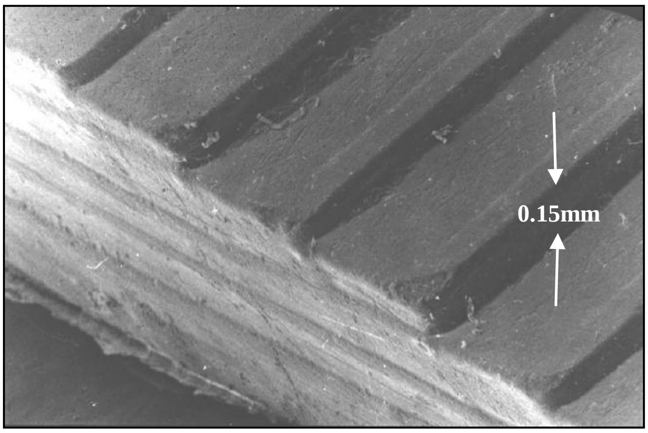

Fig 1 – Stereolithography components with 10-degree surface showing 45-micron RA roughness

Part orientation also affects the number of layers needed to construct the part within the ALM process. Fig 2 shows the same part orientated into three different positions relative to the build axis. Orientation A will require fewer layers than either orientations B or C. This will result in a quicker build, which will not only reduce part lead time, but also reduce part cost, as the cost of ALM parts is directly related to the amount of time needed to produce them.

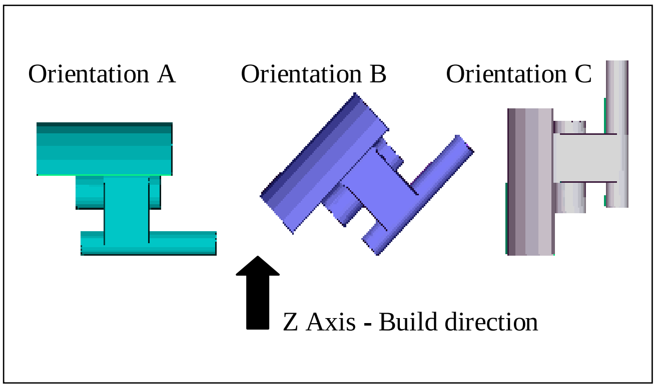

Fig 2 – Part orientation will impact on surface quality, build time and part cost

Once the optimal orientation has been established, automated software is then used to slice the STL file into discrete digital layers of data. The digital layer thickness corresponds exactly to the thickness of the build layer used in the additive layer manufacturing processes. Slice data is then fed into the ALM process starting with the bottom layer of data.

Each ALM process is different. Some processes such as Selective Laser Sintering, Selective Laser Melting and Laser Cusing work by depositing a layer of powdered material onto a movable build platform. The thickness of the material layer corresponds to the thickness of the digital slice data. The geometric data from the digital slice is then fed into the ALM machine and used to position a laser beam, which is focused onto the surface of the power. Wherever the laser comes into contact with the powder it is selectively melted. Hence, by scanning the laser beam in the X and Y axis, each layer of data can be consolidated. After the powder has been selectively melted, the movable build platform moves down in the Z-axis by one layer thickness and another layer of powder is deposited onto the surface using a recoating wiper blade. The scanning and recoating process is repeated layer-by-layer until the build is complete. The parts and then removed from the machine and lightly dressed, often using bead blasting.

Other ALM mechanisms such as Stereolithography replace the powder bed with a vat of Photocurable monomer, or replace the laser mechanism with an ink-jet printing head or extrusion head. In total there are over 30 additive layer manufacturing processes commercially available [4], producing parts in polymeric, metallic, ceramic and organic materials. However, all processes use either thermal energy or a chemical reaction to bond material together into layer. The different layer bonding mechanisms are shown below in Figure 3.

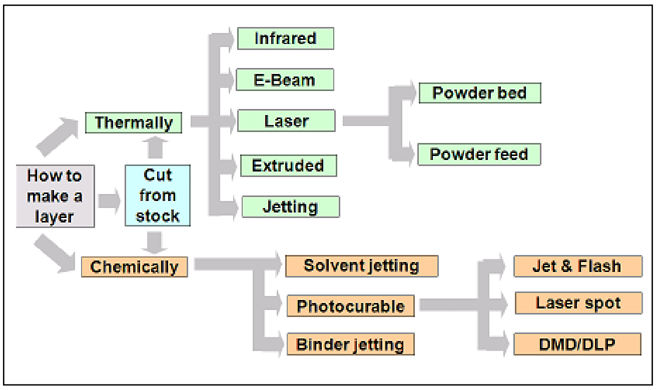

Fig 3 – Schematic representation of different additive layer bonding mechanism

1.3 Industrial applications of Additive Manufacturing

Additive Layer Manufacturing is now a billion dollar (USD) global industry [5], with technology vendors located in the USA, Europe, Scandinavia, the Middle East and Far East.

By far the largest percentage of ALM parts (80%) are still used for Rapid Prototyping (RP). Typical prototype applications include:

- Visualisation aids for engineers
- Visual aids for tool makers
- Concept models for discussion
- Quotation request models
- Presentation & marketing models
- Architectural models
- Fit & function models
- Assembly Models
- Ergonomic Studies

However, ALM parts are also being used to enable secondary downstream manufacturing operations such as casting and tooling processes, in addition to the manufacture of end use part in their own right.

2. Rapid tool inserts

One secondary application of an ALM part is to use the part as a tool cavity or as an insert within a tool cavity. This application has come to be known as Rapid Tooling (RT) [6].

Early RT cavities in the 1990's were manufactured in materials such as thermosetting polymers, which although capable of withstanding limited temperatures and pressures, were only suited to very short run production in low melting temperature polymers such as polypropylene. A typical soft RT cavity can be seen in Figure 4, which shows a simple straight pull cavity manufactured from Stereolithography resin.

Fig 4 - Stereolithography soft tool cavity (Image courtesy of Prof. Richard Hague, Loughborough University UK)

Over time new composite ALM materials were developed that allowed cavities to be made in polymer bound metallic materials, which were post process infiltrated to achieve operational densities and hardness. However, these secondary infiltration steps increased costs and lead times and had a negative effect of dimensional stability and accuracy. For these reasons 'in-direct' rapid tooling did not deliver on its early promise, and found only limited market penetration. Figure 5 shows the surface of a tool cavity produced by the Extrude Hone ProMetal in-direct tooling process in the mid 1990's.

Fig 5 - Rapid Tooling cavity made by ProMetal 3D Printing (Image courtesy of Prof. Richard Hague, Loughborough University UK)

By the late 1990's however a number of enabling technology shifts, including the developments of the fibre laser enabled much higher power densities to be achieved at the interface between the laser and the powder bed, to the point where it became possible to directly melt metal materials such as tool steel. This step change opened up the market to manufacture complex geometry tool cavity inserts directly using ALM.

2.1 Conformal heating and cooling

One of the main benefits and business drivers to the adoption of ALM is the capability to produce complex geometry parts. Because of the bottom-up layer wise method of manufacture, it is possible to use ALM to produce improbably complex geometries. One such application of this is the production of conformal heating and cooling channels 'designed' into injection moulding inserts.

The purpose of conformal heating and cooling is to introduce 'intelligent' thermal management into a tool cavity. Traditionally thermal tool management was controlled by running hot and cold water through cross drilled holes in the back of tool cavities. These holes were wherever possible located near to the tool surface. However, because it is only possible to drill straight holes, many heating and cooling channels were not positioned in the optimum location. With

ALM however, the heating and cooling channels can be manufactured to follow a conformal flow path, just under the surface of the injection moulding tool.

This methodology has now been commercialised by German ALM machine tool manufacturer Concept Laser (amongst others), who have developed a laser melting system called Laser Cusing. This technology has been optimised for the production of tool cavities and tool cavity inserts with conformal cooling [7]. The company also uses a novel, steam heating approach to rapidly cycle the tool cavity from hot to cold [8].

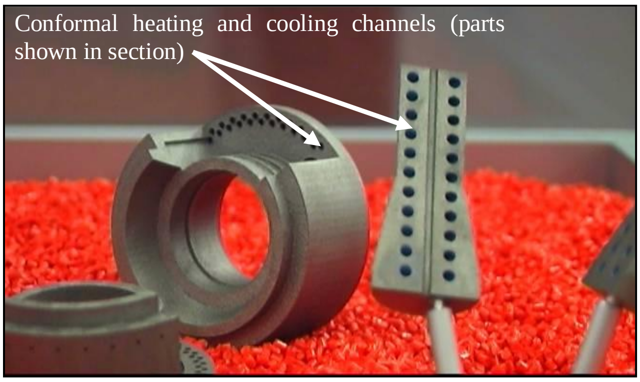

Fig 6 - Direct metal RT cavity inserts made by Concept Laser, Laser Cusing process

The benefits of conformal heating and cooling are twofold. Firstly, because it is possible to reduce the heating and cooling cycle time, the number of tool impression per minute can be increased. In essence this increased the productivity of the injection mould tool [9] Secondly, by applying conformal heating and cooling to the fine detailed features of a tool that traditionally could not be cross drilled, it is possible to improve overall thermal tool management. Hence, eliminating cold or over hot areas of the tool face resulting in improved mould part quality [10].

3. Direct metal part manufacture

Although direct metal laser sintering and melting has found only limited market acceptance within the injection moulding and die casting tool making sectors, it has started to make significant in-roads into the production engineering sector as an alternative to both CNC machining from solid billet and as an alternative to casting processes such as investment and die casting.

3.1 Material sustainability

Many CNC machined parts are produced from billet. In some cases the volume of this billet can be significantly more than the part that is to be produced. Within the aerospace sector this is called the buy-to-fly ratio. It is not uncommon for ratios of 20:1 to be experienced. In other words, for every 20 Kg of raw material purchased as a billet, only 1 Kg of material ends-up in the final part. This means that 19Kg of cutting chips (swarf) becomes a waste stream and finds its way back into the materials supply chain. For low cost and low melting temperature materials such as aluminium, this is not a significant issue. However, for more expensive and higher melting temperature materials, such as titanium, which is prevalent in aerospace, this is becoming a significant economical and logistical problem. Moreover, titanium billet stock is not readily accessible and can commend significant lead times of up to and over 12-months.

Inversely, direct metallic ALM process are highly material resource efficient, as they only use the raw material required to consolidate the final part, and in some cases a small amount of support structure [11]. Moreover, any material that is not consolidated during the ALM process can be re-used in the machine, without entering into the recycling supply chain. This material utilization factor has a number of significant business benefits. For instance, titanium billet costs approximately $50 per Kg and titanium powder suitable for ALM costs $350. However, assuming the buy-to-fly ratio of a part is greater than 7-to-1 then it is more cost effective (purely from a materials perspective, ignoring processing cost) to procure the more expensive powder. Figure 7, shows a typical ALM part made using Electron Beam Melting. This part would have a very high material waste ratio if manufactured using CNC machining.

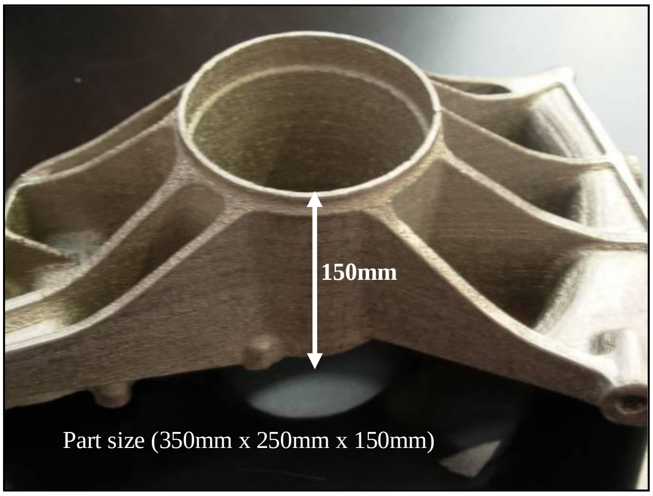

Fig 7 - Electron Beam Melted component part, with high materials waste ratio when made using CNC machining

3.2 Design for Rapid Manufacture

There are also significant business benefits to the use of ALM, which are related to design flexibility. Because of the additive wise approach to production using ALM, it is possible to manufacture highly complex geometries. This allows user to both increase the complexity of individual parts but also to manufacture assemblies of parts already integrated together, in a process known as part consolidation. Another business benefit associated with complex geometry part manufacture using ALM is surface texturing. By imparting complex micro-geometry onto the surface of parts, such as the accetabular cups shown in Figure 8, it is possible to increase the functionality of the final product. With the accetabular cups shown in Figure 8, a micro patternation is applied to the surface of the part during the layer manufacturing process. This surface texture provides a key for bone growth and promotes cell ingress into the medical implant.

Fig 8 – Accetabular cups manufactured with designed surface porosity to promote bone cell ingress

3.3 Life cycle carbon reduction

In addition to part consolidation and micro-surface patternation, ALM processes are also able to make highly complex geometries, which cannot be manufactured economically by other processes. One such application is in the manufacture of honeycomb structures and micro-lattices, as shown in Figure 9. These structures can be integrated into designs using automated software tools [12], which both reduces part weights and the amount of material required to produce a part.

In addition to the obvious benefits of minimising raw material usage during the production cycle, there are also further down-stream benefits to ALM within the supply chain.

By designing parts specifically for ALM processes it is possible to manufacture components that are both optimised in terms of their performance, but also optimised in terms of their strength to weight ratio.

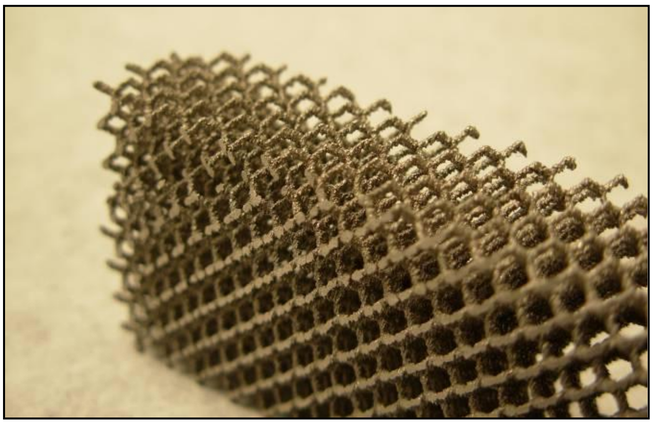

Fig 9 – Micro-lattice structure produced using electron beam melting.

Improved strength to weight ratio is particularly important in applications such as aerospace, where every additional 100kg of weight, can cost an airline over $2.5-million in fuel over the aircrafts lifecycle (based on a long haul jet covering 90-million miles)[11]. A typical example of an ALM part that has been designed for material reduction can be seen in Figure 10.

Fig 10 – Selective Laser Melted RM part designed with material optimisation

The ALM part in Figure 10 has 60% less material than the original geometry traditionally manufactured as a die casting. In terms of carbon footprint reduction, it is suggested that there are five primary environmental and sustainability benefits to the adoption of additive manufacturing [11].

1. Reducing the amount of raw material required in the supply chain. Hence, reducing the need to mine and process primary material ores.
2. Reducing the need for energy intensive and wasteful manufacturing processes such as casting,

or processes such as CNC machining which require cutting fluids.

3. By enabling the design of more efficient products with better operational performance. Such as hydraulic components with conformal fluid paths
4. By reducing the weight of transport related products that go on to contribute towards the carbon footprint of the vehicle into which they are integrated
5. By allowing parts to be manufactured closer to the point of consumption by eliminating the need for fixed tooling and centralised manufacture.

4. Direct polymer part manufacture

Many of these business and sustainability benefits also apply to polymeric ALM parts. In fact, polymeric ALM is more mature in its industrial application than metallic ALM.

4.1 Mass personalisation

There are a number of products currently being produced using polymeric ALM where the geometric data used to design the part is derived from the individual customer. This configuration of supply chain we refer to as mass personalisation. Two examples of mass personalisation are the manufacture of In-the-Ear hearing aids, as shown in Figure 11, and in the manufacture of personalised dental braces, as commercialised by Invisalign [13]

Fig 11 – In the Ear Hearing aids produced by the Envisiontec Perfactory RM process

4.2 Mass customisation

In addition to mass personalised products there is also a growth in the number of products manufactured by RM which are customised by the end user or consumer. This configuration of supply chain we call mass customisation. One area where mass customisation has been integrated with RM production, is in the realisation of computer games characters or avatars. Figure 12 shows a mass customised character from the computer game World of Warcraft. This character has been designed online by the customer and then printed to order using 3D printing, prior to shipping.

Fig 12 – Mass customised internet games avatar character designed by the consumer and produced using 3D Printing

4.3 Distributed manufacturing

One of the most significant logistical business benefits of Rapid Manufacturing comes with the elimination of tooling. As without tooling such as mould tools, jigs and fixtures it is possible to manufacture component parts concurrently at multiple geographic locations, a methodology know as distributed manufacturing. The primary benefit of distributed manufacture is the ability to shorten transportation distanced between the point of manufacture and the point of consumption. This has a number of benefits including reduced transportation leads times and associated stock holding, reduced transport costs, reduced carbon footprint and reduced stock obsolescence and risk [14].

4.4 On-line RM product fulfilment

A number of companies are already exploiting the unique characteristics of tool-less manufacturing in other ways. For examples companies such as Freedom of Creation (FOC), based in Amsterdam [15] hold no stock, but wait until they receive an order for one of their product, before instructing one of their globally distributed suppliers to manufacture the part. The part is then shipped directly to the consumer from the supplier, without ever physically coming into contact with FOC staff. To-date FOC has developed a range of home ware products including lamp shades and light fittings as shown in Figure 13, furniture such as tables and chairs and decorative items such as fruit bowls. The company has also produced fashion items such as hand bags and jewellery. In all cases the products are made directly from laser sintered nylon powder.

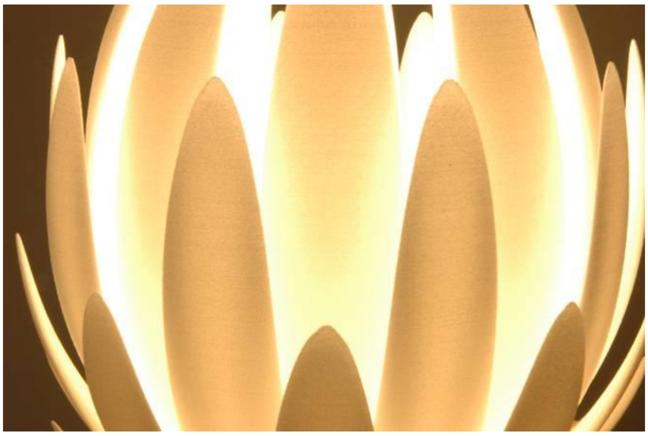

Fig 13 – Laser Sintered Nylon lamp shade manufactured using RM to order from FOC CAD data

4.5 Home based manufacture

The distributed manufacturing model adopted by Freedom of Creation has a number of economic and environmental advantages, as it significantly shortens the supply chain between design innovation and the customer. However, there may be an even shorter supply chain solution where the consumer becomes the factory.

A number of companies, including Pasadena based Desktop Factory [16] are developing low cost additive manufacturing systems for home use, as shown in Figure 14.

Fig 14 – Desktop Factory, Low cost home based ALM solution

The concept of home based additive fabrication or Fabbing is not new, and was first postulated in the early 1990s [17]. However, it has taken some 15 years for the require hardware to reach an acceptable price point, where it is within the reach of individuals rather than corporations. The concept of home based fabrication is very similar to that of internet movie of music downloads. The consumer will go on-line to a web based store and selects a product, such as an FOC lampshade, Disney cartoon character or the latest Hollywood blockbuster figurine. After credit card verification, the STL (or coloured VRML) data file will be downloaded for home based fabrications.

This model does have a number of limitations such as copyright control, brand management and liability. However, it also has some significant benefits in terms of generating revenue without the cost of fixed asset investments.

One other possibility will be the integration of home based fabrication technologies and on-line design websites such as JuJups [18]. The JuJups portal provides users with a pallet of online design tools. Users are able up upload photos and images into the JuJups portal. Images can then be positioned on products such as picture frames. Simple web based design tools can then be used to modify the size, shape, profile and texture of the picture frames. When complete the 3D data file is then sent for 3D printing internally within JuJups. However, there is no technological reason why this data could not be provided back to the customer for home based fabrications.

5 Future directions

Additive fabrication has come a long way in the last 25-years. However, it will undoubtedly go much further in the next 25-years, given the large number of commercial technology vendors, materials companies and academic research groups now engaged in the sector.

Areas of current research, which may lead to future products include the additive manufacture of embedded electronics, batteries and intelligent materials [19], the 3D printing of human tissue cells and organs [20] and the additive manufacture of intelligent materials at an atomic level [21]

6 Conclusions

In conclusion, this paper has demonstrated that in little over 25-years, since the concept of additive manufacturing first took shape, the technology has found applications across the supply chain, from concept design to mass production.

We have shown how the technology has found applications within the tool making industry for the production of tool inserts with conformal heating and cooling channels, an application driven by reduced cycle times and increased product quality. On reflection, it is unlikely that this application will have a significant impact in the current tool making or CNC machining sectors. More significant however will be the potential threat of both direct metallic

additive manufacturing on the CNC machining community and direct polymeric part manufacture on both the tool making and moulding communities.
There will always be a place for high volume polymeric and metallic part manufacture, which will be supported by traditional moulding and casting processes. However, with the advent of the internet and the increase in consumer trends towards customised and personalised products, there is also a clear business case for additive manufacturing. This business case is further justified if we take into consideration material utilization and efficiency, transportation costs and carbon footprint. Although it is some way into the future, the promise of home based manufacture will have significant implications on the traditional factory and supply chain concept.
Although many people believe that home based manufacture is little more than a dream for the future, it is worth putting the concept into context. On 22nd June 2009, Kodak stopped production of its iconic Kodachrome film. The reason being the almost exponential decline in the number of people using film based cameras compared to digital cameras. The knock on effect of this transition has also been the shift towards home based photographic printing, as opposed to laboratory based printing. In the case of Kodak the driver to change was the digital camera. In the case of the traditional supply chain, the driver to change could well be additive manufacturing.

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