How the socio-economic benefits of Rapid Manufacturing can be used to off-set the technological limitations

ABSTRACT

Much has been written about the technological capabilities and constrains of Solid Freeform Fabrication (SFF) technologies used for the manufacture of end-use component parts. This application of the technology we now know as 'Rapid, or Direct Digital Manufacturing'. In many cases, RM is benchmarked against more traditional processes such as injection moulding, die casting and more recently CNC machining, both in terms of the capabilities of the process and the resulting mechanical and geometric integrity of the resulting parts. In many cases, this activity remains the limiting factor in the justification or dismissal of RM as a disruptive technology.

In this paper the author looks beyond these *'traditional engineering metrics'* of process selection, into the socio-economic benefits of RM and how the technology can be used to enable entire new business models and supply chains. The paper looks at where RM can add value across the product life cycle, from customer engagement and new supply chain configurations to new service and supply models. The paper looks at the environmental and societal benefits of RM and how the technology can and will be used to respond to shifting global demographic and economic patterns, such as the aging population, increasing fuel costs, limited natural resources and ever changing consumer trends.

The paper draws on the Experiences of the author working with both companies to implement RM solutions and a number of Universities research projects to scope the future of this innovative and exciting technology.

INTRODUCTION

Rapid Manufacturing (RM)[i] or Direct Digital Manufacturing (DDM)[ii] are the common names given to the production of 'series' or 'end-use' component parts made using 'Additive Layer Manufacturing' (ALM) processes. Historically, ALM processes were used to manufacture prototypes and casting patterns. However, recent advances in ALM technologies and materials, now allow us to manufacture parts in polymers, ceramics and metals for a variety of production applications.

The principle of additive layer manufacturing is relatively simple. As opposed to machining, where material is removed from a solid block, or moulding where material is melted and forced into a cavity, additive processes work by 'building-up' the required geometry directly from 3D computer data, particle-by-particle, layer-by-layer, from the bottom-up.

There are many different mechanisms for both generating a single layer and also for bonding layers together. In some simple systems, layers are cut from sheet material and

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[i] - UK and European common definition
[ii] - North American common definition

bonded using adhesives or ultrasonic welding type processes. In other systems, layers are generated by melting fine powder using a laser or electron beam, and consolidating the new layer onto the previous layer by remelting. In all, there are over 30 different ALM processes marketed by over 40 different companies around the world[1].

One of the most notable advantages of RM is the potential elimination of tooling. Without the constraints of casting or moulding tools, or machining jigs and fixtures, RM provides manufacturers the ability to produce cost effective batch sizes of 'one', or the ability to manufacture parts with multiple product design iterations at no additional cost. RM is therefore seen by some as one of the most important emerging technologies that will drive the future of manufacturing in high wage economies[2].

Because RM uses layer-wise manufacturing, many of the traditional Design for Manufacture (DFM) principles no longer need apply, as parts are not made in tool cavities or held within fixtures. Therefore, RM components can be manufactured with no split lines, or with complex internal and re-entrant features. RM therefore allows for significant part consolidation, reducing manufacturing, assembly and inspection costs.

RM also allows for the manufacture of topologically optimized components, producing parts that are 'manufactured-for-design' as opposed to 'designed-for-manufacture'. This can eliminate many secondary manufacturing steps such as internal machining operations or secondary fabrication.

In principle, RM can reduce or eliminate many stages of the traditional supply chain, which reduces lead times, inventory and supply chain transaction and logistics costs.

Moreover, because RM parts are made using additive manufacturing technologies, as opposed to subtractive or formative processes, little if any waste material is generated, (with the exception of certain polymeric processes). This is particularly true of the newer direct metal powder bed processing systems. Additive manufacturing processes are therefore lean, yet agile, allowing the manufacture of low volume batches of component parts, with little manual intervention.

In recent years, there has been a significant growth in the number of companies using RM across a broad range of industrial sectors. Examples of RM applications include aerospace and automotive components, packaging, medical implants, hearing aid shells and surgical guides, and consumer products as diverse as light shades, furniture, jewellery and even football boots. However, systems are limited in terms of their production throughput, materials choice, accuracy, repeatability and cost.

However, as we will discuss in this paper, the *'true'* benefits of RM far exceed the economic potential for just low volume manufacture. In fact, the vast majority of current successful RM business applications, are in fact driven by either societal 'wants' or societal 'needs', rather than production engineering economics.

THE SOCIETAL BENEFITS OF RM

So how will RM best respond to societal wants and needs? The Technology Strategy Board[3], which represents the interests of the UK government in funding science and technology research within business, has identified three key drivers to social wellbeing around which future products and services are likely to be developed.

These are:

- The health and wellbeing of the citizen
- The security and safety of the citizen
- The environment in which the citizen lives and works

It is suggested that by focusing research efforts around these three broad themes, greater societal benefits will be achieved for the good of the UK citizen over the next 20-years. However, it could also be argued that these priorities apply globally rather than just nationally.

As a disruptive, yet enabling technology, RM has the potential to impact significantly in all these areas of research, and therefore future business opportunity. Moreover, RM is a great leveller, enabling both large and small enterprises alike to compete within the global economy to service the needs of the growing consumer base.

In order to forecast where RM could be driven by societal needs in the future, it is worth looking at current RM applications and research activity, as much of this is already aligned against these national or arguably global priorities, and will surely lead to increased volumes of RM within the future.

HOW RM IS RESPONDING TO THE HEALTH AND WELLBEING THE CITIZEN

Health and wellbeing is fundamental to our quality of life. However, if we consider the current applications of RM within healthcare, we must also consider that healthcare products and services can be driven by both ‘wants’ and ‘needs’.

Invisalign[4] is a well documented dental product manufactured by Align Technologies in the USA using ALM tooling. Although not manufactured directly using RM materials, the Invisalign business model is predicated on the flexibilities of additive manufacturing, where each dental aligner is made using a customised forming tool. However, although visually more attractive, less invasive and far more flexible in terms of orthodontist interaction than traditional dental braces, it could be argued that the Invisalign product is driven more by consumer ‘want’, rather than by consumer ‘need’, as other dental brace technologies already exist.

To a lesser degree of ‘want’ rather than ‘need’, is the demand for geometrically customised hearing aids, as seen in Figure 1. These are produced by a number of companies globally using RM, including Siemens[5], Phonak, Minerva and Starkey Laboratories. The key benefits to the user, above and beyond traditional hearing aid products, are both increased comfort and increased performance through reduced feedback. A range of RM processes are now used for hearing aid manufacture, including Stereolithography, Perfactory and Polyjet printing.

Figure 1 - Personalised RM hearing-aid shells produced using Envisiontec Perfactory

RM has also found applications in the manufacture of dental implants. However here, two separate technology solutions are being used to address both consumer 'wants' and patients 'needs'.

Sirona Dental Systems[6] uses Direct Metal Laser Sintering (DMLS) from EOS GmbH to produce CoCrMo bridges and crowns directly using patient scan data. However, by replacing the traditional investment casting approach, Sirona has managed to get the unit price of crowns below £13.50[7], this being significantly less than the cost of the traditional approach. RM is therefore being used to arguably support affordable healthcare solutions for those elements of society most in need.

Inversely, US Company Imagen Inc, a division of EX ONE[8], uses 3D Printing of binder onto noble metal powders to produce dental caps and crowns in precious metals, including gold. Although aesthetically more pleasing as a substrate than CoCrMo, this approach is clearly more expensive and driven by the customer's desire for a premium product, rather than the need for a practical dental solution.

One area where RM is being applied to healthcare as a direct result of patients needs, is in the manufacture of customised surgical implants and procedural guides. To-date both laser based and electron beam ALM systems have been validated for the manufacture of surgical implants. The MCP Selective Laser Melting process is now being used to manufacture a range of medical implants and cutting guides, including maxiofacial implants as shown in Figure 2, cranial fixings, prophetic hangers, and saw and drill guides[9].

Figure 2 – Mandible reconstruction manufactured using MCP selective laser melting

The ARCAM Electron Beam Melting Process is also being used for personalised 'patient-centric' cranial implants[10], but also in the volume production of Accetabular cups as shown in Figure 3, with embedded porosity to promote cell ingress[11].

Figure 3 – Accetabular cups manufactured using ARCAM Electron Beam Melting

Significant global research is also underway to manufacture tissue engineering scaffold and constructs using RM[12], which are customised to the individual patient[13]. This is driven by the patients need for effective healthcare.

This use of synthetic RM scaffold replaces far more invasive methods using donor material from other sites in the patient's body, reducing theatre time and potential infection.

Inversely, as a direct response to consumer 'want', Econolyst has recently engaged in a project to 3D-Print models of neonatal foetuses, directly from 3D/4D ultrasound baby scan data, as keepsakes for parents and relatives. Although considered 'simply a gimmick' by some, for worried or grieving parents these models do to some degree provide comfort and a marginally improved quality of life.

The future socioeconomic effect of healthcare on RM adoption

At this point in time we are only just scratching the surface of potential RM applications to improve healthcare delivery and increase our quality of life.

A recent medical devices and practitioners focus group facilitated by the author as part of a government fact finding exercise into emergent technologies, identified significant opportunities for RM across the healthcare sector, most notably as a direct result of the ageing and increasing population.

The UK has an ageing population. This is the result of a decline in the mortality rate and an increase in past fertility rates. This has led to a declining proportion of the population aged under 16 and an increasing proportion aged 65 and over[14].

In every year since 1901 (with the exception of 1976), there have been more births than deaths in the UK and the population has grown due to natural change. Until the mid-1990s, this natural increase was the main driver of population growth. Since the late 1990s there has still been a natural increase, but net international migration into the UK from abroad has also been an increasingly important factor in population change. The net result of these factors is that more people require affordable and responsive healthcare than ever before. This picture of population growth is mirrored across much of the developed world.

Given the tool-less flexibility and geometric freedoms of RM, the technology is well positioned to respond to the needs of these emerging groups, as in-effect, every patient is a unique shape, size, weight and density.

RM therefore becomes particularly pertinent in situations where traditional products and devices will no longer suffice the *'needs'* of the user. Examples identified during focus groups include, hand grip, tools and mobility aids for those with osteoarthritis or rheumatoid arthritis. Other applications, where human body form can be mapped onto RM part surfaces also have the potential to improve quality of life. Such applications include conformal seating surfaces for the infirmed, prophetic limb interface, trusses and support pads for degenerative muscular disorders, orthotically designed footwear, braces for fractures and dislocation realignment splints, as shown in Figure 4.

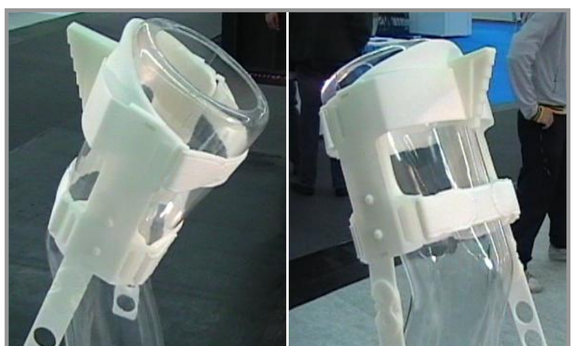

Figure 4 – personalised 'knee-brace' manufactured using Selective Laser Sintering

So is health and wellbeing a worthwhile market place for RM research and business exploitation? In 2005, the UK budget for the National Health Service was £90-billion[15].

This compares to a domestic aerospace markets of £22.7-billion[16] during the same period. In short, 4 times more was spend on healthcare in the UK than in our entire aerospace sector. It should be noted that this figure excludes private healthcare expenditure, private dental expenditure and healthcare products, services and devices sold for export.

In summary, healthcare is a large, vital and growing sector. It is people centric and driven primarily by the *'needs'* of society rather than the *'wants'* of the consumer. However, it could be argued that private healthcare is driven by both needs and wants, where patient choice is driven by purchasing power. Here, RM is a perfect fit!

RM IN RESPONSE TO THE SECURITY AND SAFETY OF THE CITIZEN

In the last 10-years, safety and security has become an almost daily concern for large divisions of the global population. These divisions may be as a result of geographically, religiously, politically or tribal differences. However, safety and security can also be far less complex and far closer to home. Our own safety and the safety and security of our families should also be seen as a key opportunity for the unique traits of Rapid Manufacturing.

A number of research initiatives have already started to look at RM as a production methodology for the manufacture of customised personal protective equipment.

Large scale pan-European *Framework Six* project 'Custom Fit', has a number of work packages investigating the use of RM as a production solution for the manufacture of personalised motorcycle crash helmets[17], using automated scanning and RM processes. RM is being used to enable the manufacture of both personalised geometry, but also impact absorbent designs such as honeycombs, which would be impossible to manufacture using traditional techniques.

Less complex crash helmets have already been produced for competition rowers by TNO in Holland[18], and for high speed ball games such as Lacrosse or hurling, as shown in Figure 5.

Figure 5 – Personalised 'sports-helmet' manufactured using Selective Laser Sintering

Another large scale initiative, involving Loughborough University in the UK, and a range of international partners is the 'SCUTA' project, which is investigating RM for the production of tailored injury prevention and performance improving projective garments, for use in sports such a taekwondo, soccer and cricket[19].

Within SCUTA, RM is being used to make conformal body armour with built in energy absorbency characteristics. The objectives being to not only provide increased protection for the athlete, but to also increase athlete performance through improved garment design. The author has also recently been engaged in a project to assess the suitability of RM as a production method for low volume personal safety products, including motorcycle, snow boarding and equestrian back protectors utilizing the design freedoms of RM to produce truly optimised products for the individual consumer.[20]

Research at Liverpool University has demonstrated the potential to manufacture energy absorbent Selective Laser Melted lattice structures, which are then laminated with carbon fibre. Early examples suggest that this combination may have better energy absorption characteristics and less damage under impact than traditional aluminium foam's. Initial application in the motorsport sector, could over time, be extended to passenger vehicles, police and security service body armour or as blast protection in off-shore or mining applications.

Other examples of where RM has been used in the manufacture of personal safety devices include the manufacture of bespoke and low volume high frequency Radio Frequency (RF) transponders for marine safety applications using selective laser melting, and selective laser sintered flood safety electrocution devices for London Underground personnel.

Future safety and security influences on RM adoption

In the future there is no doubt that RM will be deployed into conflict zones. The concept of the mobile parts hospital has already been tested with CNC technologies[21] and it is only a matter of time until direct metal powder bed or deposition process are deployed into the 'theatre of operation' to rebuild and repair broken armaments and vehicles. Moreover, as RM usage increased within military aircraft production[22], then the demand for replacement RM parts in the future will increase proportionally.

Within our everyday lives RM could also play an important future role. RM has been used for a number of years in counter-surveillance to manufacture customised housings for both video and listening devices. Such applications could easily be extended to the home user to monitor both intruders or for that matter to monitor the family!

Current research into protective personal equipment for performance athletes will also cascade down onto the high street, for every day club players and school children. We are already seeing moves towards this through the 'elite-to-high-street' project[23], where customised RM foot ware originally aimed at professional soccer players is being expanded into the mass market.

RM AND THE ENVIRONMENT IN WHICH WE LIVE AND WORK

One of the least understood areas of Rapid Manufacturing is its potential as a sustainable production technology. However, as well as the potential macro-environmental and sustainable benefits of RM, we must also consider its application within our own micro-environment, namely our homes and workplaces.

RM may not yet be in every home or office, but given disposable wealth and a desire for exclusivity, it could be in the future. Companies such as Freedom-Of-Creation, Future Factories, Kundalini and Materialise MGX, and designers such as Bathsheba Grossman and Assa Ashuach have all launched commercially successful homeware products using RM as their primary production method. Products include lamp shades, chairs, tables, paper weights, pens, jeweller and table ware, as well as handbags, carrying cases and book marks. All products designed and manufactured to enhance the micro-environment in which we live, by providing the feel-good-factor!

On a macro-scale however, RM has only recently been identified as a potential for low carbon manufacturing, a significant global issue and one that could significantly expand the future business applications for RM technology.

If we deconstruct the potential benefits of RM, we find that there are five (5) fundamental environmental drivers to the technology.

1. **Reducing energy during the manufacturing chain** - RM has to potential to replace processes where significant amounts of energy are wasted changing the phase of materials from solid to liquid, such as casting or moulding. Particularly when casting, metal is often held in a molten state for significantly longer than needed before re-solidification. Moreover, in the case of machining, many materials require the addition of cutting fluids which use both water resources and produce industrial waste. Some ALM processes on the other hand only uses the energy needed to consolidate the materials required for a part, particularly the newer direct metals processes. However, other processes remain potentially wasteful as they require material pre-heating and cooling cycles.

2. **Reducing material wastage** - Although polymeric RM processes produce waste, in terms of either used powder or support structures, many of the newer direct metal powder bed and powder feed systems can be up to 97% material efficient. This has the potential to significantly reduce the amount of scrap produced during manufacture. As an example, with aerospace machining, buy-to-fly ratios of 20:1 are not uncommon. Here, for every 20-Kg of materials purchased, 1-Kg ends up in the component parts. The remaining 19-Kg becomes scrap, which then requires costly and energy inefficient reprocessing.

   Figure 6 shows a comparison between the geometries of a diesel fuel pump manufactured using traditional casting and machining (image A) and one manufactured using RM (image B). In the case of the RM geometry (image B), the part is 60% lighter than the traditional part (image A) made from an equivalent material.

   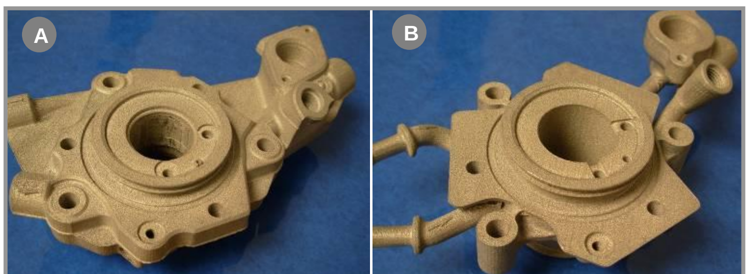

   Figure 6 – Comparison between 'traditional product design' (A) and RM product design (B), made using MCP-SLM process

3. **Reducing transportation, logistics and packaging** - RM has the potential to reduce many stages of the traditional supply chain. Because highly complex geometries can be constructed with RM, many parts can be consolidated, reducing both piece part count and assembly. Moreover, because RM requires no tooling, manufacture can be undertaken nearer to the ultimate consumer, using a methodology know as 'distributed manufacture'. The Nett effect of both distributed manufacture and a leaner supply chain is a reduction in the need for haulage, warehousing, logistics and critically, disposable packaging. It should also be noted that we have recently seen a consumer back-lash to excessive produce distribution or 'food miles', where consumers have boycotted produce that is growth many

thousands of miles away from the point of consumption. It is not unthinkable to assume that the consumer may also apply this thinking to tangible consumer goods in the future. Moreover, there is an economic argument to support distributed manufacture, as increasing fuel and energy costs will only serve to drive up the cost of goods manufactured away from the consumer base.

4. **Realizing optimised products** - Most products are not optimised, as they are 'designed-for-manufacture' rather than 'manufactured-for-design'. Because of the constraints of traditional manufacturing processes, many design objectives are curtailed. These may be optimised fluid flow channel, as shown in Figure 7, minimal material wall thickness or the elimination of ribs and bosses. Moreover, with RM, it is suggested that truly 'topologically optimised' designs could be realised, which could increase the functionality of the product, reducing wasted energy, fuel or natural resources in operation.

Figure 7 – Optimised design leading to increased product efficiency

5. **Life cycle carbon footprint** - One of the most important manufacturing considerations today is life-cycle engineering, where the designer must consider both the implications of the part through its service life and the end of life disposal of the part. For both aerospace and automotive components this means that we must now consider the life-cycle implication of a component in terms of its carbon footprint and the long-term impact of the part on the environment. With RM, by optimising the design of a product and manufacturing it with absolute minimum material, it is possible to significantly degrees the weight of parts, as already seen in Figure 6. However, if that part happens to be an aircraft or automotive components, then the life cycle carbon foot print of the vehicle will be significantly reduced using RM[24], as the component part made using RM will weigh less generating a lower fuel burden.

In summary it is believed that by coupling multiple attributes of RM together, environmentally advantageous products and business models will be designed and produced. Econolyst have recently engaged in a research project with Loughborough University, The Boeing Company, Virgin Atlantic, Caterpillar, Delphi, Bentley Motor Company and MCP Tooling Technologies to investigate the concept of sustainable production using RM. The project entitled 'ATKINS', will investigate the sustainable benefits of RM, from raw materials production and utilisation, to manufacturing energy consumption and optimised and topologically designed components. The overall objective is to build a low-carbon RM production cell validated for use in passenger and commercial automotive applications and in aerospace.

What other environmental pressures will impact on the adoption of RM

As we have already mentioned, increasing fuel costs will in the future drive the need for both lower energy manufacturing processes and manufacturing nearer to the point of consumption. Additionally, increasing globalization and the *'china-effect'* will continue to stretch the global supply of commodity materials such as copper and steel. Compounded with this, we also know that global reserves of materials such as copper are in terminal decline, hence, necessitating the need to find more resource efficient production technologies. In future, it is not inconceivable to think that some materials will be extracted in a powder form and remain in a powder form until processed using RM technologies, rather than the current methodology of extraction, billet manufacture, melting, atomisation and powder production.

On a more micro rather than macro-environmental scale we must also consider the changing 'social environment' in which we live and work. Our social environment is ever changing, with constantly evolving consumer trends driven by our desire to be either an individual, or part of a group or sub-culture. RM has the potential to service the needs of these fast moving consumer groups and subcultures.

One such example of RM servicing a developing sub-culture is the internet based www.figureprints.com which has a strategic alliance with gaming software developers, Blizzard Entertainment Inc of Irvin California. Through the figureprints web site, members of the *'World-of-Warcraft'* gaming community (or virtual environment) can order full colour 1/18th scale 3D models of games characters for little over $100. Interestingly, this is a fully closed loop business model between Blizzard Entertainment and Figureprints, where the community user does not gain access to the digital data used to realise their gaming character. The inverse business model is used by www.fabjectory.com, where members of the Internet community *'Second-life'* are able to export their own character data from the community and up-load these to the Fabjectory website for Rapid Manufacture. This business model is set to grow exponentially in September 2008 with the planned release of the long awaited internet game 'Spore' from Electronic Arts. In this future game, member of the virtual environment will be able to capture 3D data of their characters at any time, and export these as full colour 3D-PLY files. These will then be printed for a fee by companies such as Fabjectory and many others.

A natural extension of this model will then be home printing, which will not only allow individualised product manufacture, but also has the potential to reduce both manufacturing miles and excessive and unnecessary product packaging. Both Cornell University of Ithaca USA (www.fabathome.org) and Bath University in the UK (www.reprap.org) have both developed low cost RM machines aimed at the home market, both based on open source machine design and open source control software.

In a far more commercial context, Pasadena based Desk-Top-Factory (www.desktopfactory.com), a spin out of IdeaLab, will launch the worlds first sub-$5,000 fully automated 3D Printing systems in the 3rd quarter of 2008. The 125ci, as shown in Figure 8, is a powder based systems using a deposition roller heated with a simple halogen bulb, a build platform and an annealing plate. The machine design is aimed at being simple, robust and suited to the non-technical home based user.

Figure 8 – Desk Top Factory 125ci (developmental machine Pasadena Jan 08)

It is inevitable then that with ever increasing home 3D CAD usage through packages such as Google Sketch-up, computer games that exports 3D STL data such as ‘Spoor’ and home based 3D printing machines such as Desk-Top-Factory; RM will play its part in reducing the carbon footprint of the consumer. However, potentially it is the industrial user engaged in sectors such as aerospace or automotive manufacture that will see the greatest ‘positive’ environmental impact resulting from RM adoption.

CONCLUSIONS

Within this paper we have provided an alternative view of the drivers for the future adoption of RM. We has postulated that a significant proportion of current RM applications are in fact driven by the wants and needs of the consumer, rather than the economic needs of the production or manufacturing engineer and that this trend is likely to accelerate in the near future. This will be driven by an increased access to digital content creation sources such as home based CAD, gaming software and on-line data archives and libraries.

We have also seen that given the flexibility, reconfigurability and sustainability potential, RM could support many of the primary production demands of future society. Namely, societies demands for a cleaner more inclusive world, in which the citizen is healthy, safe and secure.

Traditionally RM has been seen as an economic cost effective production technology used as an alternative to injection moulding, machining and casting. Within this paper it is suggested that RM is actually better placed to ‘compliment’ these existing technologies through the production of new products and services, not yet realised through traditional manufacturing processes.

Moreover, it could be argued that the drivers to implemented RM into traditional supply chains as a disruptive technology are actually the result of individuals experienced in Rapid Prototyping. Here, ALM systems are used to build form, fit and function models prior to investment in fixed assets such as tooling. Hence, much of the knowledgeable RM community at present stems from the RP community, which by its very nature was engaged in traditional production supply chains, such as moulding casting and machining.

In the future however, the demand from RM will be driven from much further up the supply chain, at a point where the production methodology becomes almost irrelevant to customer. In this future scenario, customers and consumers will merge as one and the critical attributes of a product will be its carbon footprint and ‘customer-centric’ fitness for purpose. The author strongly believes that this vision of the future presents the greatest opportunity for Rapid Manufacturing technology application.

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