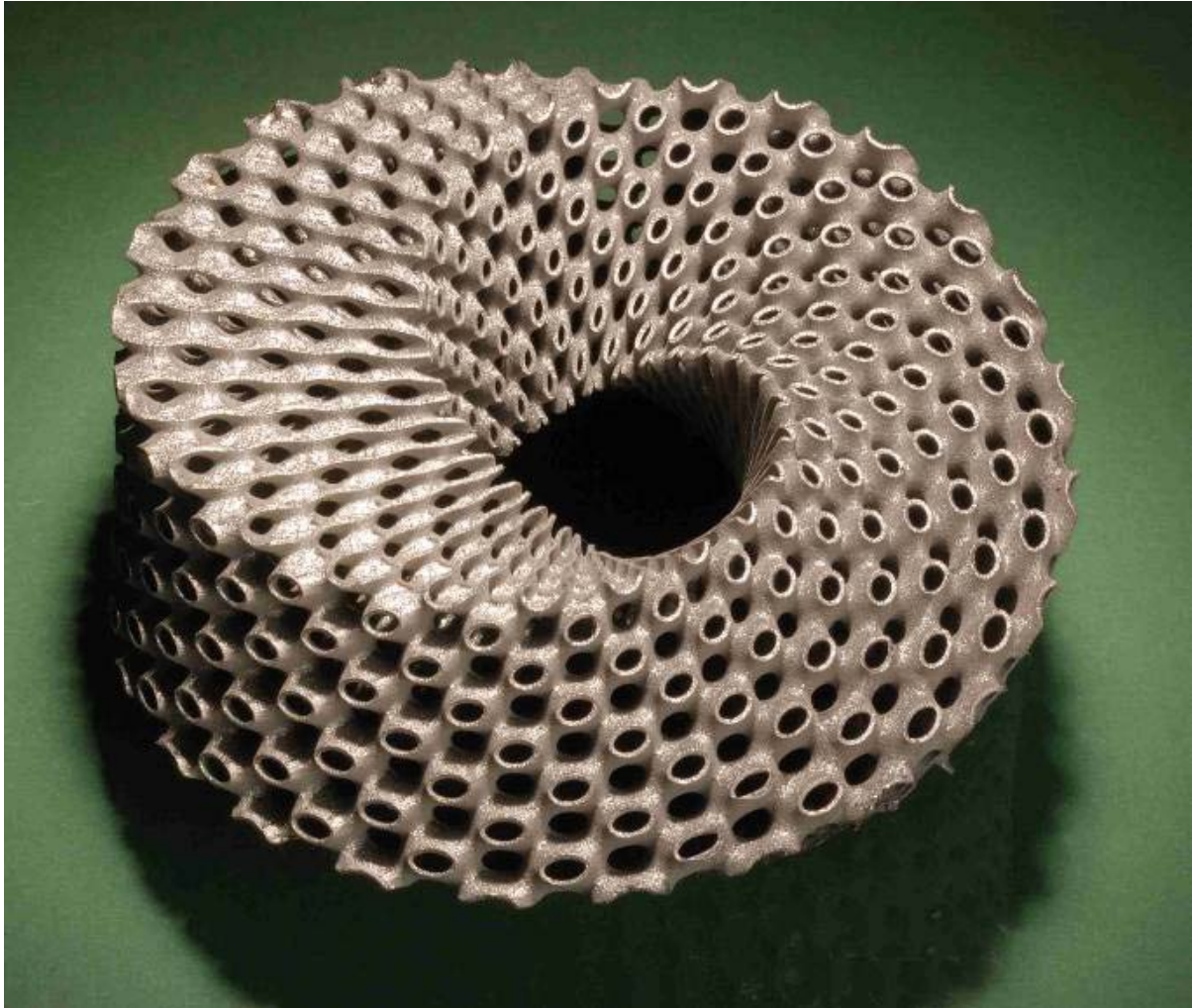


**Rapid Manufacturing
Strategic Research Agenda 2010
A Future Vision for RM**



**The Exploitation of World Class RM
by the EU**

Prepared by the Rapid Manufacturing Platform

Executive Summary

Overview and Vision

This Strategic Research Agenda (SRA) has been produced as an update to the SRA produced by the **Rapid Manufacturing Platform** dated 3rd November 2006. Although the broad direction of the Rapid Manufacturing (RM) field has not changed, particular areas have changed in priority. For example, the barriers to adoption and exploitation, though similar, are not identical to those identified in 2006.

RM continues to be an exciting field of research and considerable progress has been made over recent years. The term RM is modified from Rapid Prototyping (RP), where the technologies were used more for demonstration rather than function. The techniques are now being exploited in manufacture, and this is where industry will truly benefit. If there is one long term goal underpinning this SRA, it is **the installation of RM as a viable alternative manufacturing route to conventional processing**. RM has many advantages over such processes, but its level of maturity is significantly behind that of machining, casting, forging etc.

This Strategic Research Agenda (SRA) is part of the activities of the Rapid Manufacturing Platform which was initiated by key industrial players, supported by the European Commission and recommended by the *Manufuture* ETP. There is also alignment with the Factories of the Future Private Public Partnership. The aim of the Rapid Manufacturing Platform is to accelerate the mainstream exploitation of RM within the EU, and to address the 'Grand Challenges', such as society issues and the environment.

The Definition of RM - RM is defined as the use of a computer automated additive manufacturing process to reliably construct parts that are used directly as finished products or components. RM is a form of manufacturing parts, similar to machining, casting, forging, and welded fabrication.

Objectives

The main objective of this SRA is to define the barriers to adoption and exploitation of RM to enable the following:

- **Commercial gain** through the use of RM processes resulting in:
 - An increase in turnover.
 - An increase in jobs.
- **The tackling of the 'Grand Challenges'** such as:
 - The reduction of the detrimental human impact on the environment.
 - Issues in society such as the overall quality of life.

The barriers identified are not absolute, and it should be emphasised that they are opportunities to be exploited.

RM is a disruptive approach and has potential to replace other forms of manufacturing and create its own markets. This results in a high potential for RM to assist the EU in competing with lower wage rate economies. Such manufacturing techniques are the key to securing manufacturing within the EU. To ensure this future it is, therefore, vital that the EU is significantly ahead in the development of RM technologies. This would then create increases in business turnover and the number of jobs related to RM.

The 'Grand Challenges' that we face are significant, however, RM has the potential to play a significant part in striving toward solutions. RM can have a significant effect on a number of environmental issues. For example, RM enables the light-weighting of transportation, reducing carbon dioxide and other emissions. It is the responsibility of society to assist those less able, and RM can facilitate this. For example, the process agility of RM can allow the mass customisation of medical implants resulting in more long term solutions for an ageing population.

Barriers/Opportunities for Exploitation

This SRA has been drawn up to list the barriers to exploitation, but should also be viewed as a list of opportunities. The true benefits of RM are yet to be realised on a large scale, and therefore, there is the potential for significant commercial gain through addressing the areas below.

The four main barrier areas to the mass exploitation of RM are:

- A. Cost.
- B. Process Capability and Stability.
- C. Implementation.
- D. Environmental Benefits.

This list is not exhaustive and some of the topics are being addressed on a small scale, however, if the EU is to remain at the forefront of RM exploitation significant effort is required to overcome these barriers.

Insert barriers diagram here

The Future of RM

There are two levels to RM:

Fundamental - Replacement of the conventional approach.

Unique - The creation of new and unique opportunities.

RM has been used at an entry level to replace more conventional techniques. It has competed and won, in business case terms, and has been used in production. As RM matures this will happen more often and development will be required to achieve this.

There is however, another level of application. Because of the layered nature of the part generation, RM can deliver unique materials, structures and properties.

There are also other initiatives in niche areas, for example in the biomedical field, that are moving science forward. For example the printing or growth of organs using RM, and the creation of assemblies, and potentially functioning systems.

1 Overview and Vision

1.1 Background

This Strategic Research Agenda (SRA) has been produced as an update to the SRA produced by the **Rapid Manufacturing Platform** dated 3rd November 2006. Although the broad direction of the Rapid Manufacturing (RM) field has not changed, particular areas have changed in priority. For example, the barriers to adoption and exploitation, though similar, are not identical to those identified in 2006.

RM continues to be an exciting field of research and considerable progress has been made over recent years. The term RM is modified from Rapid Prototyping (RP), where the technologies were used more for demonstration rather than function. The techniques are now being exploited in manufacture, and this is where industry will truly benefit. If there is one long term goal underpinning this SRA, it is **the installation of RM as a viable alternative manufacturing route to conventional processing**. RM has many advantages over such processes, but its level of maturity is significantly behind that of machining, casting, forging etc.

This document will attempt to give a basic assessment of where RM is in terms of technical readiness, and manufacturing maturity. Technology Readiness Level (TRL) will be used in general terms to define this more quantitatively. TRL evaluations and procedures are being used increasingly across industry to evaluate the readiness of a process for exploitation, and to set out the requirements for a process to deliver on a commercial basis. Some examples of EC funded projects will be given, including case studies of commercial exploitation and the step change technological benefits these projects have delivered.

This SRA will then present the barriers and opportunities for mass adoption and exploitation for RM. In a similar way to the 2006 SRA this will be built around a small number of topics within which the fundamental issues lie. This document does not seek to detail the problems or to define the solutions. In that regard RM will be treated as a single subject, whether it be for plastics, metallics, ceramics or other materials. It does however, outline the areas for improvement that will, if addressed, ensure that the EU continues to define the state of the art in this exciting field. In conclusion, a future vision will be presented around the practical delivery of commercial benefit through RM, and the potential of the processes to deliver both products and services that would be impossible through more conventional means.

This SRA was compiled through a number of industrially driven sources and events, and has been adopted by the Board of the Rapid Manufacturing platform whose objective is to provide advice and recommendations to the European Commission on Rapid Manufacturing, also known as Additive Manufacturing (AM).

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It is a stated objective of the EC that the development and exploitation of advanced manufacturing techniques is a high priority for the EU. The threat to the European Manufacturing base of the low wage rate economies will only be mitigated using strategies based on advanced manufacturing. RM represents advanced manufacturing in arguably its purest form. RM provides incredible design flexibility with a process that has a minimal environmental footprint. Components can be designed for function, and to minimise material utilisation, which can be made consuming no water, chemicals or tooling.

The Definition of RM - RM is defined as the use of a computer automated additive manufacturing process to reliably construct parts that are used directly as finished products or components. RM is a form of manufacturing parts, similar to machining, casting, forging, and welded fabrication.

1.2 Alignment with ManuFuture and Factories of the Future

Insert text here.

1.3 The Opportunity

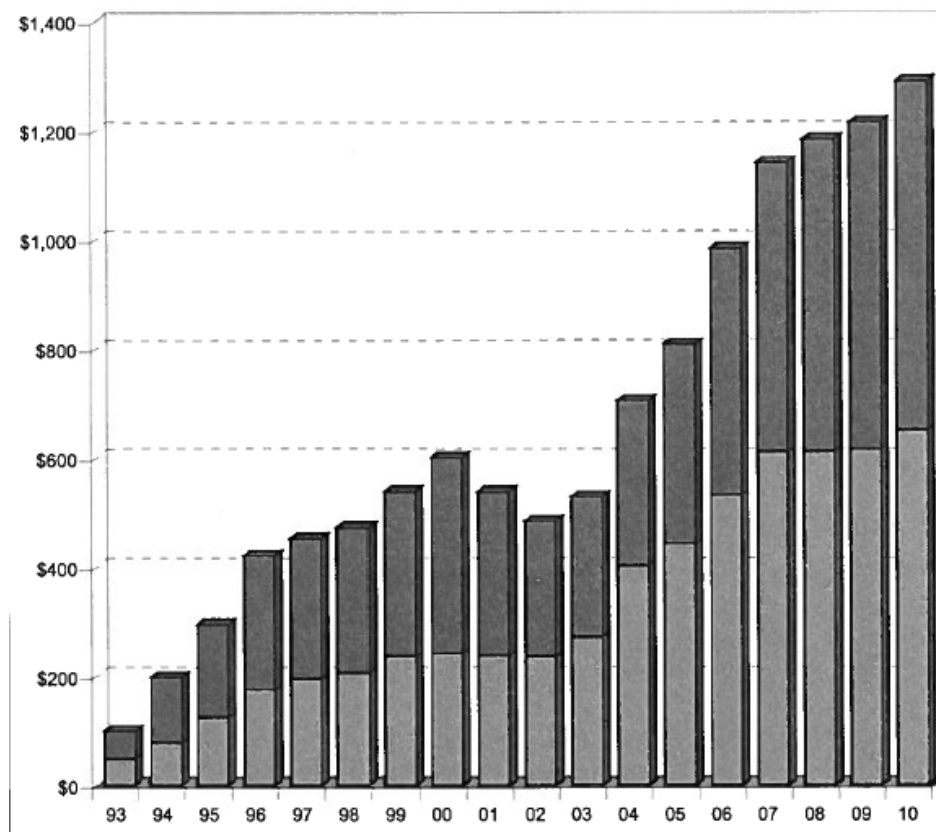


Figure 1 The Additive Manufacturing market since 1993 (x axis). The currency on the y axis is in millions of US dollars. The lower portion of the bars indicate 'products', and the upper proportion indicate 'services'. The 2010 value has been predicted. Courtesy Wohlers Associates Inc.

Figure 1 shows the RM market growth from 1993. It is evident that, excluding extraordinary events such as those around 2001 and 2008, there has been massive growth year on year in the RM sector.

The majority of these revenues are concerned with products and services associated with the production of plastic parts. There is still much research and development to do to penetrate existing markets and create new opportunities, in the field of plastics. There is also the metallics RM business which is catching up with the plastics related components. Metallic parts also have great potential. The forging and castings market worldwide is of the order of \$100 Billion. Machining parts from billet is also a particular target for metallic based RM. As with the plastics market, the penetration of exiting markets and the creation of new areas of application to exploit the unique attributes of RM is the aim.

2 Objectives

The main objective of this SRA is to define the barriers to adoption and exploitation of RM to enable the following:

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RM is a disruptive approach and has potential to replace other forms of manufacturing and create its own markets. This results in a high potential for RM to assist the EU in competing with lower wage rate economies. Such manufacturing techniques are the key to securing manufacturing within the EU. To ensure this future it is, therefore, vital that the EU is significantly ahead in the development of RM technologies. This would then create increases in business turnover and the number of jobs related to RM.

The 'Grand Challenges' that we face are significant, however, RM has the potential to play a significant part in striving toward solutions. RM can have a significant effect on a number of environmental issues. For example, RM enables the light-weighting of transportation, reducing carbon dioxide and other emissions. It is the responsibility of society to assist those less able, and RM can facilitate this. For example, the process agility of RM can allow the mass customisation of medical implants resulting in more long term solutions for an ageing population.

3 Current Position of Rapid Manufacturing

3.1 The Manufacturing Maturity of Rapid Manufacturing

To gauge the current manufacturing maturity of RM it is useful to measure RM applications against the Technology Readiness Level (TRL) scale. Following initial development from NASA and other organisations and companies, industry has widely accepted the TRL scale as a way of measuring the maturity of the application of technology. The Aerospace Sector, that has particular interest in RM, has been one of the quickest to adopt this approach, with Rolls-Royce being a good example. Their approach has been to define the process on a number of levels. A more manufacturing orientated version of their TRL scale has been defined as their Manufacturing Capability Readiness Level (MCRL) approach. A schematic of this is presented as Figure 2. For this comparison TRL will be equated with MCRL.

Considering the RM development and exploitation that is in the public domain, it is evident that individual applications are at all points of this scale. For example, the creation of single crystal turbine blades could be viewed as being at TRL 1, and the manufacture of simple plastic components at TRL 9. Overall however, the following conclusions can be made:

- RM is in the 'productionisation' phase. Applications have been proven and are awaiting exploitation. This would equate to approximately TRL 4.
- The RM of plastics is, in general, at a higher TRL scale than that of metallics. Other materials are generally lower than this, for example ceramics.

Programme phase	MCRL	State of development
Phase 3 Production implementation	9	Fully production capable process qualified on full range of parts over extended period (all Business Case metrics achieved)
	8	Fully production capable (FAIR Stage 2) process qualified on full range of parts over significant run lengths
	7	Capability and rate confirmed (FAIR Stage 1 without concessions) via economic run lengths on production parts
Phase 2 Pre-production	6	Process optimised for capability and rate using production equipment
	5	Basic capability demonstrated using production equipment
Phase 1 Technology assessment and proving	4	Process validated in laboratory using representative development equipment
	3	Experimental proof of concept completed
	2	Applicability and validity of concept described and vetted, or demonstrated
	1	Process concept proposed with scientific foundation

Figure 2 Manufacturing Capability Readiness Level (MCRL), part of the Technology Readiness Level (TRL) approach. Courtesy Rolls-Royce Plc. FAIR is a Rolls-Royce acronym.

The above conclusions are by no means absolute, there are many applications at all levels. However, for RM to progress, the large amount of applications that are approaching TRL 4 need to be exploited for commercial gain.

TRL's 4 to 6 are traditionally the key areas to developing a process for production, and are therefore, the main areas where applications fail. It is comparatively easy and cost effective to prove that an application can be done in a laboratory. It requires a lot more development and investment to achieve process capability and stability in full production.

3.2 Myths Surrounding RM

The following are myths that surround RM:

- There is not unlimited design freedom, BUT there is great design freedom.
- It is not 'rapid', BUT it is very agile.
- AM does not yet have 100% material usage, BUT we are getting close.
- AM will not be suitable for all applications, BUT it is currently especially good for small batches of complex and/or personalised parts.

These points are very general comments but there has to be some realism to the expectations from RM, and the promotion of RM should over-promise its capabilities.

3.3 Exploitation from EC Funded Projects

Insert text here

4 Barriers/Opportunities for the Mass Adoption and Exploitation of RM

4.1 Overview

This section forms the main body of this SRA. It has been compiled with input from all areas of the RM development chain, throughout the EU. Although this has predominantly been industry lead, the views of academia have been incorporated as appropriate. The process has involved initial scoping through the RM Platform, which has then been followed up by initiatives on a national level. These have then been drawn together to produce an RM SRA for the EU. For example, the Additive Manufacturing Network (AM Net) initiative in the UK has been set up to bring together industry and academia to input into this SRA. Following these consultations, the draft document has been circulated for widespread feedback, and revision. The result is a clear, concise and informed view of what is needed to get the most out of RM.

This SRA has been drawn up to list the barriers to exploitation, but should also be viewed as a list of opportunities. The true benefits of RM are yet to be realised on a large scale, and therefore, there is the potential for significant commercial gain through addressing the areas below.

The four main barrier areas to the mass exploitation of RM are:

- A. Cost.**
- B. Process Capability and Stability.**
- C. Implementation.**
- D. Environmental Benefits.**

This list is not exhaustive and some of the topics are being addressed on a small scale, however, if the EU is to remain at the forefront of RM exploitation significant effort is required to overcome these barriers.

Insert diagram here with four barriers and issues coming from this.

4.2 A: Cost

Cost is clearly a key driver, and barrier, for the adoption of RM. For new technologies to be adopted in production clear and significant benefits need to be evident, because of the investment and risk associated with their implementation. A clear cost reduction is one of these benefits, and is usually a required element.

Key areas for cost reduction include:

- Processing speed/productivity.
 - Quicker layers.
 - Faster turnaround.
- Reduction in equipment cost.
- Reduction in material cost and improvement in material utilisation.
- Reduction in post-processing.
- A reduction in scrap.

Figure 3 shows a schematic of a simplified RM cost model. The main cost of RM products is in the process. This cost includes the labour involved, and the depreciation of the machine. To minimise these costs, productivity improvements need to be implemented. RM can be a slow process because of the layered nature of the techniques. Development to decrease the time to create each layer, the overall time between layers, and start up and shut down time, should therefore, be a priority.

Although equipment cost is reducing, there are systems available for 10k€ or less, equipment can be 500k€ or more. The difference is usually the material and quality requirements. For business propositions to be pursued in current financial climates, machines are being depreciated over shorter timescales, such as five or three years, perhaps less. This results in the cost of the machine having more of an influence over the cost of the product.

Material cost is a key factor. Reliable material at a competitive commercial cost is key for the development of RM. Material suppliers are fulfilling these requirements, but this needs to continue and develop. The tying in of material suppliers to the machine provider is not necessarily a strategy that is beneficial for RM. It generally increases cost, and single source supply increases the risk to industry. Many companies will not pursue an application if there is such an arrangement.

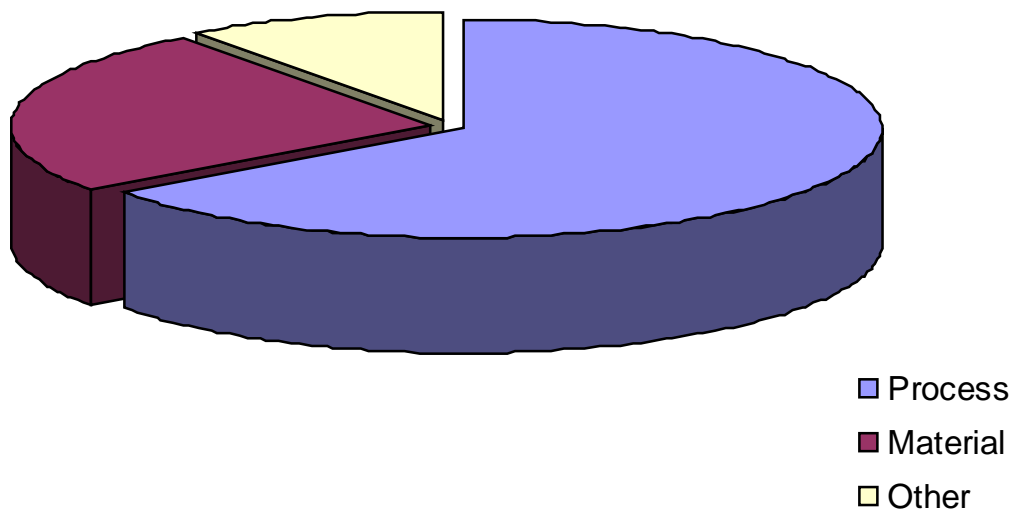


Figure 3 A schematic showing a simplified cost model for the production of components using RM processes.

Other factors contribute to cost such as post-processing, heat treatment and final machining (if necessary), non-destructive testing, geometrical assessment, batch testing etc. There are ways to reduce these costs, such as improving the product from the RM machines to minimise post-processing, and ensuring a consistency of product to minimise quality checking procedures.

4.3 B: Process Capability and Stability

The TRL approach, referenced above, aims to achieve capability and stability in production. Process capability is ultimately concerned with the part being fit for purpose. Process stability development works towards 'right every time' production.

Key areas regarding process **capability** include:

- Material capability, quality and performance.
- Larger parts.
- Improve surface finish.
- Geometrical stability.
- Smaller parts and features.
- Hybrid processing.
- Assemblies.

- 'Right first time' processing:
 - Capability to insert CAD file and process.
 - Will require data and guidelines package from empirical sources and modelling.

Material performance is key to the performance of a part. It seems that each end user goes through an extensive validation exercise, including both static and fatigue testing in the case of metallics, to confirm the material performance. The performance of cast and wrought material is well documented, and it is necessary for future acceptance that RM material is viewed in the same way. The hygroscopic nature of some plastic RM components, and the consistency of ceramic parts can cause problems. These issues are being overcome but consistency is a problem. RM parts have the potential to out-perform, or perform differently, to conventionally created components, however efforts to **replace** cast material, for example, with RM material has produced results. This is because it is a replacement issue rather than the qualification of what is seen as a 'new' material. Material quality needs to be consistent 'every time', and can vary especially if processing parameters have not been fixed.

Larger parts need to be created through the **scale-up** of the processes. RM techniques that involve feeding the material using a head or nozzle arrangement are more suitable for this development than powder bed based processes. However, because of the advantages of powder bed techniques, scaling up from the traditional 250mm cube has market opportunity, especially in the Aerospace Sector.

Surface finish has a big effect on cost if it means that the part can be taken off the platform and used. The need for machining inaccessible areas can be an issue. The capability to create accurate and more complex geometries reduces scrap and increases value, respectively.

Development into **smaller parts and features** has been carried out. The handling of powder particle sizes less than 10 microns can be difficult, but some companies have achieved results with small powders or different approaches.

Hybrid processing, the addition of features to existing substrates to create parts, can result in cost improvements, because of the reduction in forging complexity and the amount of material required, for example. Business cases for the replacement of **assemblies** are often attractive because there is no joining required.

Key areas regarding **process stability** include the stability of:

- Material feedstock.
- Build to build consistency.
- From one batch to a future batch.
- From one platform to another of the same platform.
- From one platform to a different platform.

If the material fed into the RM system is inconsistent then the part created will be inconsistent. There also has to be a consistency from build to consecutive build. Production also has the requirement that, should the build requirements be interrupted, the original procedures can be successfully followed. This is also true if the same equipment from the same supplier is used. There is a lesser need for the transfer of parameters from a system supplied by one manufacturer to a similar system supplied by another. This kind of consistency would enable the creation of standard material performance data, as is available for cast metallics.

4.4 C: Implementation

RM technologies could be perceived as being in the 'productionisation' phase, therefore the implementation of a holistic production approach needs to be developed.

Key areas regarding implementation include:

- Standards
- Supply chain
 - Reduced lead times.
 - Design flexibility.
 - Personalised product.
 - Reduce part miles.
 - Reduction of recurring costs, e.g. tooling.
 - Reduced inventory.
- Education
 - Designers need knowledge and software tools
 - Next generation
 - Disseminate the successes

Standards have been slowly created for RM, however, a recent initiative from ASTM has brought together RM developers and users from the around the globe with the aim to standardise RM.

Supply chain developments have highlighted advantages of RM. For example, simply providing powder to a machine on-site can provide parts of varied size and shape, with great flexibility. This can reduce lead times, recurring costs, the need for inventory and 'part miles', reducing the environmental impact of the components.

There is a great need to **educate** the current and next generation of designers to what can be achieved with RM. The most benefit from RM is usually achieved when the parts are redesigned for the RM process. Using conventional design thinking of 'design for manufacture', if applied to RM, does not get the most out of the approach. There is also a need to further publicise the successes, and build political momentum for the adoption of RM.

4.5 D: Environmental Benefits

Future manufacturing will be measured increasingly on its environmental footprint. RM has distinct advantages over more conventional processing. The areas below need to be investigated, quantified, improved and exploited.

Key areas regarding **environmental areas** include:

- Material utilisation/recycling validation.
- Development of light-weighting for transport applications.
- Development of light-weighting for reduction in transport footprint.
- Processing improvements:
 - More efficient heat sources.
 - Higher productivity processing.
 - Reduction of in-process losses.
- 'Clean' and 'Sustainable' processing development.

The near 100% **material utilisation** involved in RM is a distinct advantage to wasteful processes such as machining. 'Buy to use' ratios can be 20:1 by weight, or higher. This is clearly not sustainable in the long term from an environmental or economic stand point. More effort is also required in the validation and standardisation of the batch to batch recycling of materials.

Light-weighting can provide a number of benefits. In transport applications this can improve fuel efficiency and performance, potentially reducing consumption and emissions. It reduces the amount of material required and can also reduce the impact of transportation. The compression of supply chains can also have environmental benefits.

RM techniques have room for improvement regarding their overall approach. For example, the heat sources used, for example lasers, need to be made more electrically efficient. The processes are too slow and therefore need to be more productive to reduce resource usage. As with most processes there is room for improvement regarding in-process losses.

RM techniques are '**clean**' in that they do not consume water, tooling, chemicals and are near 100% material efficient. True **Sustainability** is achieved through not consuming natural resources. RM can reduce the use of material, assist in the reuse and recycling through improved design. More work needs to be done however, in the recycling of material using RM processes after the part has finished its natural usage life. This could involve melting of used parts, the monitoring and control of material chemistry, and the atomisation of this material to create feedstock for RM systems. The value chain is key, because if the material is fed back into the same level or higher, true sustainability can be approached.

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5 The Future for Rapid Manufacturing

5.1 Overview

There are two levels to RM:

Fundamental - Replacement of the conventional approach.

Unique - The creation of new and unique opportunities.

RM has been used at an entry level to replace more conventional techniques. It has competed and won, in business case terms, and has been used in production. As RM matures this will happen more often and development will be required to achieve this.

There is however, another level of application. Because of the layered nature of the part generation, RM can deliver unique materials, structures and properties.

There are also other initiatives in niche areas, for example in the biomedical field, that are moving science forward. Figure 4 shows a machine that can '3D print human organs'.

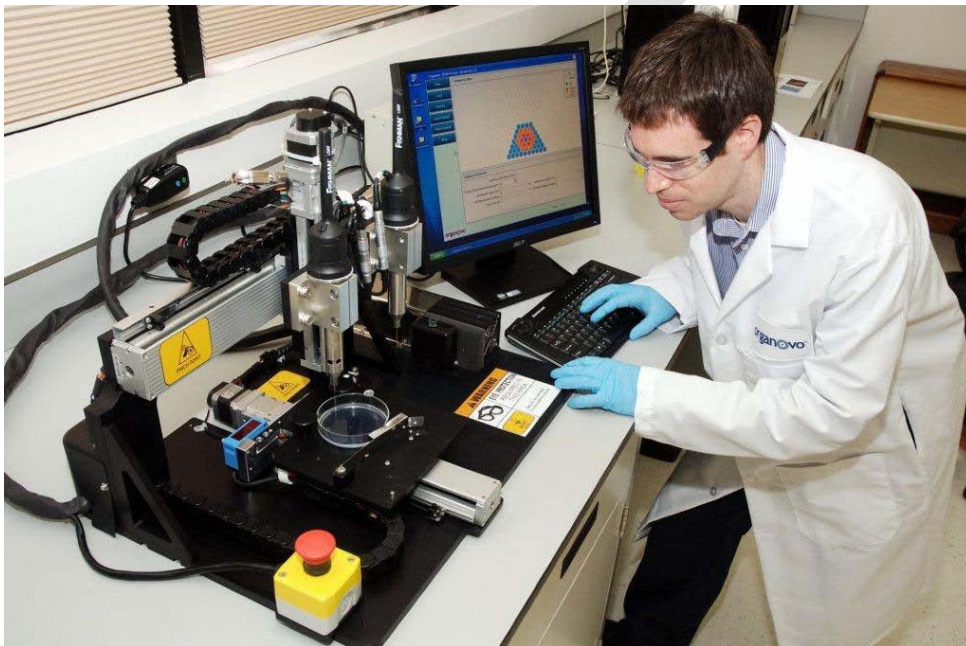


Figure 4 A commercially available 'human organ printing' RM machine. Courtesy Organovo Inc.

5.2 Short to Medium Term - Productionisation

The vision of many in the industry is a clean factory with row upon row of RM machines, all quietly and efficiently delivering product with minimal human intervention. This is being done, see Figure 5, to a certain extent with mainly 'polymeric' applications. There are metallic RM job shops that have multiple machines, but they tend to have around three rather than thirty. Where RM can be very productive, and this falls into where the EU should be, is highly advanced, low labour intensive, environmentally sensitive, manufacturing. If a large shop floor can be maintained by very few staff, wage rates do not have a significant effect on cost, and hence the EU can compete on more of a level playing field with low wage rate economies.



Figure 5 A modern RM facility, where RM machines produce parts with minimal intervention. Courtesy Materialise.

The barriers to productionisation have been mentioned above in all of the four areas, but are mainly to do with taking proven concepts at TRL4 and moving them to TRL 7 to 9. There is an investment barrier here, because of the amount of capital and effort needed to put a product into production. The whole supply chain also needs to be developed, from material supply to reliable RM systems to post-processing.

5.3 Medium to Long Term

In the medium to long term the unique aspects of RM will be used to add even more value. There are opportunities in:

- Highly complex parts.
- Parts that contain complex internal features.
- Hollow or internally reinforced parts.
- Functionally graded structures in terms of design or material.
- Novel materials, such as shape memory alloys, metallic glasses, 'single' crystal alloys, and advanced polymers with high performance, for example high glass transition temperature.
- The creation of assemblies, and potentially working systems.

There is also a vision to avoid the creation of parts altogether and just grow your functioning system using RM. Airbus have replaced a dual duct that had eighteen different parts with one RM part. Whole systems could be grown in the future,. These would be simple to start off with but could get as complex as a jet engine (!).