Rapid Manufacturing as a tool for agile manufacturing: application and implementation perspectives

RICHARD J BATEMAN[§] [*] AND KAI CHENG[§]

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Abstract

Manufacturing engineers and technologists around the globe are already well familiar with manufacturing methodologies and systems developments in the last part of the twentieth century. Many are probably also familiar with the current state of Rapid Prototyping (RP) technologies, especially in the areas of concept model making and prototype development. They may not however, be so familiar with the more recent developments of these technologies towards Rapid Manufacturing (RM) and the directions which the applications of RM technologies are taking for agile manufacturing purposes in particular. This paper critically reviews the various technologies currently available, outlines development trends in RM, discusses the approach, application and implementation perspectives by which these RM technologies are applied for increasing agility and responsiveness in manufacturing. Furthermore, the paper describes two case study examples to further illustrate the application scenarios in agile manufacturing before concluding remarks.

Keywords

e-Manufacture, rapid prototyping, rapid manufacturing, agile manufacture

1. Introduction

The current movement towards a global economy is generally accepted as a 'golden opportunity' for companies to expand their business into a whole new range of markets. This globalisation is however, something of a 'double-edged sword'. New technologies like the Internet and World Wide Web (WWW) make it possible for manufacturing companies of any size to easily expand their target market to include almost anywhere else in the world which has Internet/WWW capability. The associated costs and efforts involved can be almost negligible (especially when compared with the equivalent costs of expansion in the pre-Internet era). The downside to this ease of access to those new

[§] Affiliation: Advanced Manufacturing Technology Research Group (AMTRG), School of Technology, Leeds Metropolitan University, City Campus, Leeds, LS1 3HE, UK

[*] Corresponding author: email rjbateman@clara.co.uk

potential customers is that it is now just as easy for any other competitor company in any other part of the world to do exactly the same and enter ones own market – thus as the market 'opportunities' increase, so to does the number of direct competitors.

The increase in competition within the global economy has created new pressures on manufacturers to meet the challenge of delivering new customised products which will satisfy increasingly sophisticated consumer demands. The time taken to design, manufacture and deliver a new product to market becomes in many cases crucial, with any delay increasing the risk of failure of the business rather than just being a minor setback with the late launch of the product.

Manufacturing engineers and technologists around the world are familiar with the 'smarter' technologies and methodologies which appeared over the last few decades of the twentieth century as we progressed from Mass Production (MP) through Flexible Manufacturing systems (FMS), Computer Integrated Manufacture (CIM), Lean Manufacture (LM), Just-in-Time (JIT) and Concurrent Engineering (CE) to arrive were we stand now with Agile Manufacturing (AM). Implementation of these types of methods and technologies has generally led to substantial improvements in manufacturing flexibility, efficiency and shorter times-to-market [Cheng, 2005].

Movements to speed up the 'product development cycle' have led to the introduction of computer based design technologies like Computer Aided Design (CAD) and Virtual Reality (VR) aimed specifically at shortening the *design* phase of the development cycle. By allowing the development of 'virtual' models which can be viewed, modified and in some cases even 'tested' in a totally electronic environment these systems have undoubtedly shortened some parts of the design stage. However, in some cases a dichotomy between computer-literate designers with little or no experience of manufacturing and manufacturing engineers with practical manufacturing experience has opened up.

As part of the transition from the design phase to the production phase, it is generally necessary to create one or more *physical* prototypes to allow the demonstration, evaluation and testing of the proposed product. This creation of prototypes has traditionally been a highly skilled and time consuming task often accounting for a high proportion of the design phase. The *direct* creation of concept models and physical prototypes became possible with the development of Rapid Prototyping (RP) technologies which take the three dimensional electronic CAD models of the intended product, process the electronic model into a series of electronic cross-sectional 'slices' (Figure 1) and then use these slices to 'instruct' a RP machine to build up the model by adding shaped layers of material to create the finished physical model.

Figure 1 - The process of creating a 'rapid prototype'

The next section briefly describes the different types of existing Rapid Prototyping technologies and the impact of RP technology in product development.

2. Rapid Manufacturing Technologies and Methods

In the widest use of the term, Rapid Prototyping (RP) groups together the various technologies developed to speedily turn 'virtual' computer models into real physical prototypes and falls into two basic types.

Material removal processes are the more conventional types and involve the removal of material from a solid block or blank usually by some kind of computer controlled 'machining' process like milling, drilling or Electric Discharge Machining (EDM).

In contrast, *material addition* RP processes essentially work by adding material to create a very thin layer which corresponds to the cross-sectional shape of the object at that point, with each subsequent layer being created on the top of the previous layer so that the part is built up in a laminar fashion, from the bottom of the object to the top of the object.

From the perspective of Rapid Prototyping, the main disadvantage of creating parts by removing material from a solid block is that all structures e.g. holes, slots, cut-outs, etc. can only be made by working from the surface inwards. If internal voids are required like those for closed 'honeycomb' structures (which allow substantial amounts of mass to be removed from the object whilst still retaining the rigidity when compared with a solid block), then this will require the material from the honeycomb cells to be machined from one surface of the block, with a second covering part then being manufactured and attached to enclose the cells. Thus the manufacturing technology used means that the design of the object must consist of a minimum of two parts and some post manufacturing assembly process is necessary.

Using an additive process however, internal structures (no matter how complex) are simply built up by including them in the cross-section of the object at the required places. With this type of process it also becomes possible to create single piece objects with internal structures which would be impossible to manufacture (as a single piece) by any other method. The necessity for additional processing and assembly in objects made by material removal processes is a major reason some researchers [Hopkinson et al, 2006] include only additive processes in their definition of what constitutes Rapid Manufacturing (RM) - since those methods are the only ones which can produce objects in their finished form in what is essentially a single manufacturing operation.

2.1 Rapid Prototyping by Material Addition

There about 25 variations of rapid prototyping technologies currently in existence but using the classification system developed by Kai and Fai in 1997 [Kai, 1997], these can be grouped together into processes using either liquid, powdered or solid materials as starting materials, the three basic groups being:

- *liquid monomers* which are cured (e.g. by laser or UV light) layer by layer into solid polymers,
- *powdered materials* that are bonded (e.g. by heat or adhesive) layer by layer,
- layers cut from *sheet material* laminated together to form the solid object.

The overall process has common key characteristics whichever method is used, with the first part of the process following the same basic steps of

(i) geometric modelling using a CAD system to create a computer model of the object and define its enclosed volume,

(ii) tessellation of the geometric model, where the CAD model is converted into a format that approximates its *surfaces* by multiple facets - usually triangles or polygons - which is usually then stored in an STL format file. This file format is named after Stereo Lithography, one of the primary technologies developed for rapid prototyping by 3D Systems.

(iii) the slicing of the model in the STL file to closely spaced horizontal layers - convention for slicing dictates the slices to be in the x-y plane with the layering to occur in the z-axis.

The sliced model is then used by whichever technology to create the object in a layer by layer fashion.

2.1.1 Liquid Based Systems

The most well known liquid-based system uses a process known as *Stereo Lithography* (SL). In this process, an ultraviolet (UV) laser beam is used to scan the surface of a vat of photo-sensitive polymer resin. The UV light causes the resin to solidify (cure) in the shape of the layer of the part (as dictated by the data from the STL file). The lowest slice is supported by a platform which is then lowered by the thickness of one slice, allowing the resin to form another layer on top. The process is repeated, each layer bonding to the previous layer until the object is completed.

2.1.2 Powder Based Systems

Another process - *Three Dimensional Printing* (3DP) - this time using powdered starting material was developed at the Massachusetts Institute of Technology (MIT) utilising ink-jet printer technology where an ink-jet style printer head is used to 'print' an adhesive binder onto successive layers of powder.

Developed by the University of Texas and working in a similar manner, *Selective Laser Sintering* (SLS) uses a variety of powders and a mechanism similar to that used by stereo lithography to selectively melt or sinter layers of powder with a carbon dioxide laser. Again, each layer is supported on a platform which lowers by the thickness of a layer and a new layer of powder is created over the top by rollers. The loose powder around the object supports any overhangs, etc. in the design. The use of powdered materials allows many more materials to be available including some metal powders, many plastics and some ceramics. The strength and porosity of the object can be controlled by scanning speed and power.

2.1.3 Solid Based Systems

The two main methods of solid material based RP systems are *Laminated Object Manufacturing* (LOM) and *Fused Deposition Modelling* (FDM).

Laminated Object Modelling (LOM) essentially works by laser cutting cross sectional layers from some form of sheet material (e.g. paper or plastic) which is supplied on rolls spooled between two rollers. The material usually has some form of adhesive backing which can be peeled off to allow the layers to be stuck together to create the object.

FDM machines use a filament of wax or polymer which is extruded onto a platform by an extrusion head (similar in process to a 'hot-glue' gun) to build up the x-y shape of the layer. The platform is then moved down and the next layers extruded on top of the previous layers. Since the material requires a small amount of time to cool and re-solidify during which it may flex or droop due to gravity, the controlling software creates additional supporting 'structures' which are built up as required to support any overhangs, etc. These supports are generally created in a different material from the object and then removed as part of the finishing process of the object.

Whilst these rapid prototyping technologies undoubtedly represent a major step forward in manufacturing technology, a recent survey of current technologies and processes used in rapid prototyping [Yan & Gu, 1996] highlighted a number of problems with the accuracy of parts made, the limited number of materials available and the mechanical performance of the objects made.

2.2 Rapid Tooling

The use of RP technologies to create moulds or patterns for small batch production quantities falls under the group term *Rapid Tool Making* (RTM) [Groover, 2002]. Tooling of the type used for injection moulding or investment casting can either be directly created (depending on the RP system and its available materials) or parts can fabricated which can then be used to take moulds from for subsequent low volume production runs.

Parts can be directly fabricated some form of plastic material using RP machines and this part can then be used to make moulds e.g. from silicon rubber, for small batch production purposes or to allow creation in materials other than those available with the particular RP system. With some materials, moulds can be made directly and then spray coated with metal to speedily produce injection moulds suitable for small production runs. Some RP methods – especially those using a wax based material like FDM – are particularly suited to the direct creation of wax 'patterns' which can then be directly used in conventional investment casting processes. These systems are often used in the jewellery and medical parts industry (Figure 2) to allow creation of one-off designs tailored for individual customers.

Figure 2. Unimatic FDM machine creating hip replacement 'pattern' parts

Whatever the method of tooling production used, Rapid Prototyping technologies are helping fill a gap in the tooling production market at the small batch production end where the cost of producing tooling by conventional means for small batches only was prohibitive and often led to small volume products being deemed economically unviable.

2.3 Current Uses of RP Technologies

Rapid Prototyping systems are becoming a necessary item of equipment for manufacturers the world over. The reductions in time and effort to the design and development stages of the manufacturing process made possible by Rapid Prototyping systems have led to year-on-year growth of the numbers of RP systems (of whatever type) being purchased and used around the world. Figure 3 shows the distribution of Rapid Prototyping systems in the world.

Figure 3 – Installed RP Systems Worldwide 2004 (Wohlers, 2004)

Figure 4 shows the various different types of use to which RP systems are being put to by those companies which have invested in them.

Figure 4 – Typical uses to which RP Technology is put (Wohlers, 2004)

2.4 Rapid Manufacturing

As one would expect, the various manufacturers are working towards the solution of the problems and the current generation of machines and materials have lead to the use of the term 'rapid manufacturing' beginning to replace rapid prototyping in the literature on this subject.

Now, a group of technologies collectively known as *Rapid Manufacturing* (RM) are being developed to shorten both the design and production phases, and promise to revolutionize many conventional manufacturing processes.

The next section examines some areas where RM technologies either already are, or could be with appropriate development, affecting the concept of how, where and what manufacturing is.

3. Manufacturing Agility & Responsiveness and the Promise of Rapid Manufacturing Technologies

Existing Rapid Prototyping and Rapid Tooling technologies have already had significant impact on global manufacturing – particularly in the speeding up of the design and development phases - but arguably their use has been mostly focused on improvements in conventional manufacturing processes.

The layer-wise way in which these technologies build objects offers exciting opportunities for manufacturing in new and innovative ways to utilize the strengths and the *unique* capabilities of the technologies. Viewing RM technologies simply as potential 'direct replacements' for existing manufacturing technologies (once they have caught up or surpassed existing manufacturing technologies in terms of materials, speed, cost, etc.) will lead to failure to capitalize on the uniqueness of these technologies and mean major opportunities will be lost in the drive for ever more agile manufacturing capability.

The remainder of this section examines some areas (Figure 5) which could be made possible by adapting and developing RP type technologies for manufacturing purposes beyond the way in which they are currently generally viewed – i.e. increasing manufacturing agility, enhancing mass customization, multi-functional materials manufacturing and 'single-operation' manufacture of highly integrated products.

Figure 5. Increasing manufacturing agility using RM methods

3.1 Direct Replacement

One path which some companies have already taken involves the use of some RP technology as a direct replacement for current manufacturing technologies. In a 'straight fight' against conventional mass production technologies, the current technical limits (cost/speed/materials) of RP machines means that they could not yet compete on a direct level. However some cases demonstrating (admittedly) limited opportunities for use of RP machines for the direct manufacture of parts in a manufacturing process have already occurred.

One such example [Wohlers, 2005] took place when the MG Rover UK company required a small number of plastic clips (approx. 1,800) for production of one of their cars. With the fabrication of the necessary tooling and conventional manufacturing by injection moulding the clips taking around six weeks, the company took the decision to manufacture the clips (six batches of 300 parts per time) using their laser sintering RP machine - taking a mere 48 hours. Manufacturing parts in this way may appear very expensive on a cost per individual part basis, but from the wider perspective the costs saved on tooling (not to mention the immediate requirement for the parts) shows this not always to be the case. MG Rover saved weeks of manufacturing time and around £54,000.

Current limits of RP technologies suggest that for the moment cases where RP technologies can successfully be used as direct replacements for conventional mass manufacturing methods may be limited to 'special cases', but that the number of instances of special cases is set to rise.

3.2 Variability in Manufacturing Capacity

One constant thorn in the side of mass manufacturers is unexpected variance in demand. Problems incurred with under- or over-production of parts are the stuff of legend in the manufacturing world, sometimes lack of small, low-value parts (e.g. wheel-nuts) can bring a production line to a standstill. Opportunities may exist for the use of Rapid Manufacturing technologies to 'top-up' shortfall in such parts and produce the extra requirement when demand exceeds forecast.

Figure 6. Use of RM to vary manufacturing capacity

Figure 6 shows an hypothetical case where the total number of parts required is sourced from a combination of a basic forecast amount manufactured conventionally (e.g. by injection moulding) but with additional parts being made by RM means when additional un-forecast demand creates additional demand. The higher manufacturing costs due to use of RM methods can be offset against the costs of 'panic' manufacturing, transport, storage and handling costs, and the trade-off between these two methods used to cost optimise the typical level of requirement.

3.3 Flexibility in Design

The ability of additive type RM technologies has some potential to reach the goals of Mass Customisation (MC) [Tseng, 2001] and increase customisation of manufactured parts down to individual customer or part level without increase in manufacturing costs normally associated with customisation.

Figure 7. Customisation of a consumer product [Bateman & Cheng, 2002]

Figure 7 shows a simple example scenario proposed by the authors [Bateman & Cheng, 2002] in which RM technology is used in a high street store to customise or 'individualise' a consumer product like a briefcase. The briefcase itself is mass produced by conventional means with RM made parts being used only at the point where the customer 'interfaces' with the product – namely the handle. The geometry of the customers hand is optically scanned, this data used to calculate the appropriate 'shape' for the grip, which is then produced by an RM machine (in the back of the store) and when completed snapped into the handle – resulting in a customized briefcase for the customer. The perceived added-value for this service allows the additional costs of production to be offset by charging a higher price for the product. The possibility to use RM technology in the high-street in this way probably revolves around the level of innovation and creativity which the designer of the product can include into the product/service to generate the appropriate level of *perceived* added-value (fashion based industries are particularly successful at generating high levels of perceived added-value in their products).

3.4 New methods for change, maintenance and repair

Use of additive process (esp. LENS) to repair existing parts or add extra bits (e.g. flange or bracket) onto stock item – sort of 'post-manufacture manufacturing' – in same materials with same properties, etc.

Figure 8. F1 Suspension bracket directly manufactured by LENS process (image courtesy of TCT)

3.5 New Structures

The material addition nature of RM technologies opens up possibilities of designing new *structures* which are completely 'un-make-able' using conventional technologies. For example new of designs of turbine blades with complex internal cooling structures could be manufactured directly e.g. the internal 'pipes' or 'channels' used for cooling or heating could be made to follow much more complex paths, changing diameter or cross-sectional shape as required. This could allow for improved heat exchange performance (by increasing internal surface area) when compared with conventionally cast turbine blades which have internal cooling pipes added after casting by drilling or EDM (Figure 9)

Figure 9. Conventional and RM manufactured turbine blades

By material addition, the possibility to consolidate of many parts into one and thus manufacture in a single operation with no subsequent assembly required. Use of certain technologies may even allow for manufacture of items which include moving parts – Figure 10 shows a fully functioning concept model of a bearing with ball bearings manufactured in-situ (supported and kept separate during the 'printing' process by the powder).

Figure 10. Example 'working' bearing – produced by Z Corporation

The possibility of manufacturing complex objects with moving parts using only a single material and in a single manufacturing operation has great potential for easing problems with recycling at the end of the product life – something of great interest as we move towards the 'closed-loop material economy' [Priess, 2005] where materials will become ever more scarce and recycling simply in order to find materials for new manufacture becomes reality.

3.6 Non-homogenous Materials

Some RM technologies offer the real possibility of changing the chemical composition of the material as it is added to the part to give different properties to different parts of the object. New structures could be made using *non-homogenous* materials where it is possible to 'design-in' the material properties of individual areas of an object as required e.g. hard for surfaces, flexible where springiness is required, etc. In addition to being manufactured in one operation new structures e.g. with fully functioning internal springs become possible. Figure 11 shows an early example of what is possible using some current single-material Rapid Prototyping machines. The object was created by London Manufacturing Centre as a 'business card' to demonstrate some of the possibilities that already exist.

Figure 11. Product created with internal springing (single material)

The potential to direct manufacture similar structures in metal varying the chemistry of the material used at any point to give the desired properties opens many exiting opportunities for future design of structures and objects which are currently impossible to manufacture either in one operation or in single parts. A recent development by Conductive Inkjet Technologies (CIT) allows the direct printing of electrical conductors using a special conductive 'ink' which offers the possibility of directly printing antennae for applications like mobile phone or RFID tags. One client company has already used this technology to print a fine heater/defroster element directly onto a motorcycle helmet visor (in a manner which would not be possible by conventional means) still retaining the flexibility of the visor.

3.7 Increases in Agility by Location

Assuming RM technologies follow a typical technology evolution 'S' curve [Rogers, 1995], increases in agility in manufacturing by flexibility in *location* will become available - once the technologies become sufficiently mature and user-friendly to be 'all-in-one-box'. Already one Rapid Prototyping machine manufacturer [3D systems] advertise the fact that their concept modelling machines come with castors on just like a photocopier (so it can be moved around extremely easily) and once it arrives wherever it needed, it 'just needs to be plugged in and it's ready to go'.

Once this kind of portability is developed in RM technologies, the possibility to quickly and efficiently move the entire manufacturing capability to wherever the manufacturing needs to take place – even the creation of 'mobile manufacturing facilities' becomes feasible. This principle of moving the facility to the location where the 'output' is needed rather than transporting raw materials and goods to and from the facility is already well established. Such implementations as mobile operating theatres and the building of temporary cement plants near large construction sites (to avoid the environmentally damaging effects of large numbers of journeys of cement trucks) are already widely used, however, careful analysis is needed to identify those cases where it is more cost effective to transport 'small' machine components, and build manufacturing machine on site than to transport large finished objects from distant manufacturing facilities.

The construction industry is host to a variety of research projects experimenting with new and varied methods of manufacture. Large scale manufacturing on-site 'problems' like the fabrication of composite beams for large construction projects have already been solved using a 'manufacture-on-site' method [Brooks, 1999], and the 'FutureHome' project [Wing & Atkin, 2002] in which modular parts for buildings can be manufactured in an off-site factory and then transported to the building site for assembly. Pushing the rapid manufacture by material addition concept even further, some groups [Koshnevis et al, 2001] have experimenting with material addition type techniques and developing materials suitable for the direct 'manufacture' of buildings. Building materials typically take much longer to solidify than the plastic type materials used in Rapid Prototyping, so a second *Contour Crafting (CC)* process is necessary which uses robotic tools to finish the added material into the 'shape' required.

3.8 Increases in Agility by Scale

Given the appropriate impetus, material addition type RM technologies could be developed to create very large scale objects as a normal manufacturing process. Many large objects are currently manufactured in many hundreds of smaller components and then assembled, for example the wings of commercial passenger aircraft contain thousands of individually fabricated parts which are then riveted or bonded together.

BAE Systems recently unveiled an aircraft fuselage made from a single piece of carbon fibre composite [Excell, 2005]. Although this structure was manufactured in the conventional moulding manner normally used with composites, there is no reason (in principle at least) why additive type RM technology could not be used to manufacture such a large product in a layer-by-layer manner. The design for a directly manufactured aircraft wing could include internal functional voids for fuel tanks, control systems, electrical wiring, de-icing systems, etc. and as outlined above, could be made from a non-homogenous material (where the material composition is varied to suit the specific function of the wing area) and designed with new structures which would improve the mechanical properties of the wing (strength, stiffness, etc.) at the same time as decreasing its mass.

To overcome operational issues like the physical to the speed of material addition for large objects, the use of *multi-axis printing* (i.e. in x, y and z planes not just in z-plane like at present) may be required and the use of *multiple* printer heads could also be needed to achieve the speeds of fabrication necessary for commercial manufacturing of large scale objects.

3.9 Possibilities for the Far Future?

Hungarian born mathematician John von Neumann (1903-1957) proposed the concept of self reproducing machines for the von Neumann probe. von Neumann proposed that rather than manufacturing large numbers of exploratory probes to explore (and possibly colonise) the vastness of space, a more efficient method would be to be to create *self-replicating machines* which in addition to exploration would search out and use materials to construct replicas of themselves which would then follow a different path of exploration. The use of self-replicating (sometimes called 'universal constructor') machines may seem far fetched, but it is a concept which NASA has been taking seriously for may years [Freitas & Gilbreath,1980] and continues to receive much serious discussion [Zykoz et al, 2005] [Adams & Lipson, 2004] [McKay et al, 1996] and a number of research groups are already exploring RM type technologies for just this purpose.

The idea of true Universal Constructor machines is familiar to anyone who has seen an episode of Star trek where 'replicator' machines build create complete items clothing, weapons, food, etc. on an atom-by-atom basis. This level of sophistication is of course still only available in science fiction but in 2000 IBM took what might be the first steps using 35 xenon atoms to create the letters IBM using a scanning tunnelling electron microscope (Figure 12) [IBM Research, 2000], And many groups

Figure 12. IBM logo built from 35 individual atoms (image courtesy of IBM)

like the RepRap project group [RepRap, 2005] have already begun designing low-cost RP machines which will be used to fabricate the necessary parts to construct a replicate of itself. The aim of these projects is to try to make real the concept of the home or *personal factory* [Hinzmann, 1996] where general purpose RM machines become so cheap and easily available they can be 'found in every home'.

4. Sample Applications

There are any number of scenarios where RM technologies could be used to change, improve or innovate manufacturing – the two following case studies arose from a previous research project [Bateman, 2005] and demonstrate possible innovative implementations of RM technology in the context of modern manufacturing era.

4.1 The 'ClutchAbility' RM scenario

The company ClutchAbility Ltd (CAL) (based on a real company who assisted with the project) is a provider of specialist high performance race and rally clutches, and this system was developed with the aim of exploring how the use of RM type technology might be used to increase the capability of an SME to offer extended and customized product range without the increased overheads normally associated with larger product ranges. The company offer a number of different clutch solutions for different engine/gearbox combinations suiting the majority of customers requirements in most areas of motor sport, but a small number of customers with non-standard requirements find the costs of having a one-off customized clutch manufactured for their specific application extremely prohibitive. The CAL company has only a small staff with non having the Computer Aided Design (CAD) expertise necessary for creating new CAD models of the customized parts.

Figure 13. The 'ClutchAbility' RM scenario

A normal race or rally clutch consists mainly consists of standard parts with the only differences being in those areas where the clutch 'interfaces' with the engine or gearbox e.g. the gearbox main input shaft. The CAL system was developed to allow the input of spline parameters into the system via a simple input screen so that these could then be used to modify a 'blank' CAD model to the suit required spline pattern by a specially designed computer programme. The modified CAD model is then sent to a local machine shop via email for manufacture. Figure 13 shows sample scenes from this process.

4.2 The 'wydiwyg.co.uk' scenario

Wydiwyg.co.uk is a web-based virtual organisation designed to allow customers to download a simple free mini-CAD programme with which they can design their own products (offline) without the expense and complication of a full-blown CAD programme. Once the customers are satisfied with their design, they can upload the CAD file to the wydiwyg site, choose a manufacturing outlet close to their locale where the product can be manufactured (not forgetting the important step of paying for it!) and collected in the next day or two or at their convenience.

Figure 14. The 'wydywig.co.uk' scenario

A major requirement for the full implementation of this case is the existence of a nation-wide network of rapid manufacturing outlets so that the customer is never far from one whatever their location. Currently this network does not of course exist, but some authorities on RP [Wohlers, 2005] are predicting the increasing ease of use and reducing purchase cost of some RP machines may lead to these machines appearing 'in the High Street' and that High Street 'copy-shops' are ideally placed for this.

5. Conclusions

That there is enormous potential for material addition type Rapid Manufacturing technologies to become genuine mainstream manufacturing technologies and take their place amongst all the existing conventional manufacturing technologies is not really open to question. The real questions revolve around what directions any development should take and to what uses these machines can and will be put - and thus what capabilities and functionality we can give them to allow us to make full use of the new possibilities offered by these technologies.

There remains much work to be done in development of these RM technologies but the potential exists for these material addition technologies to be used in a wide variety areas and in new and innovative ways, e.g. creating products and parts which cannot be manufactured by any existing method, using designs which will fully exploit the strengths and new possibilities inherent in material addition RM technologies, rather than being developed as simple replacements for existing manufacturing methods.

It is probably true to say that current development of Rapid Prototyping technologies are driven primarily by how these technologies are viewed – i.e. as concept model making or prototyping machines – so will any development will primarily be focussed on how to develop a better version of the existing machine, rather than how to develop the machine to extend the *capability envelope* to 'do different things' rather than 'do the same things but be better at it'.

To develop RP technologies into what might be termed 'proper' mainstream manufacturing machines we must overcome the psychological hurdles and begin to examine the *genuine* manufacturing possibilities these RM machines have to offer and help redirect the direction in which RM is developing. Evolution needs evolutionary pressures or drivers to ensure change – i.e. if any future development in RM technology is to take the necessary developmental directions then the appropriate ‘pressure’ needs to be brought to bear by us, the potential users ‘requiring’ increased research into materials, improvements in the functioning of the technologies (i.e. increases in speed and lowering of costs), improvements in the capabilities of the machines e.g. to create objects in more than one material and to allow intelligent addition of components like computer chips, electrical components by robotic arms *during* the process of manufacture (so that for example Radio Frequency Identification (RFID) tags can be embedded into manufactured objects to create so-called ‘intelligent products [Karkkainen et all, 2003] by encapsulating the tag) but without interrupting the material addition process.

Figure 15 shows some of the necessary stakeholders which could be brought together using a proposed web portal (the ‘Creatorium’) to build a *virtual community* with the aim of identifying and steering future directions of development in RM technologies – i.e. to provide the ‘evolutionary pressure’ necessary for the development of RM technologies along mainstream manufacturing lines, with the aim of increasing such desirable characteristics as agility, responsiveness and innovation through the use of RM technologies.

Figure 15. The ‘Creatorium’ web portal [Bateman, 2005]

The possibilities opened up by material addition manufacture will also require a new philosophy of design-for-rapid manufacture which dispenses with many of the current limitations in design-for-manufacture philosophy (which are only there to compensate for the limitations imposed by the conventional manufacturing processes).

Psychological *barriers to change* in the way of thinking about how and where manufacturing is to be done and how products can be designed will be considerable and formidable –many of these constraints have been with us since the beginning of the industrial revolution and are so ingrained that we no longer see them as artificial constraints but as ‘the way to do things’. After all, the first step in ‘thinking outside the box’ is to realise that there is a box!

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FIGURES

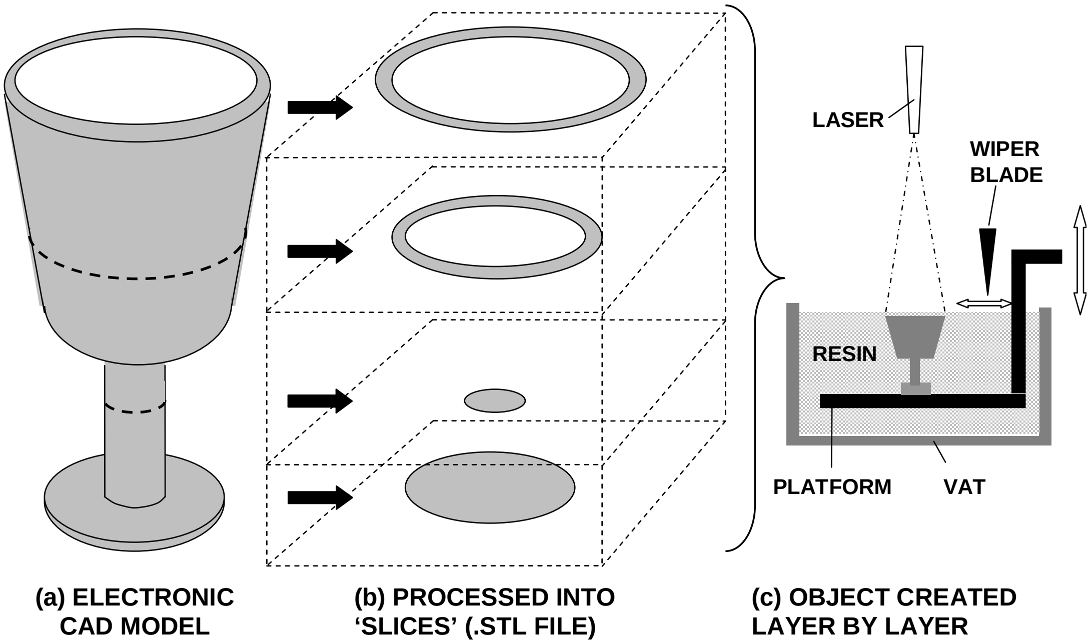


Figure 1 – The process of creating a 'rapid prototype'

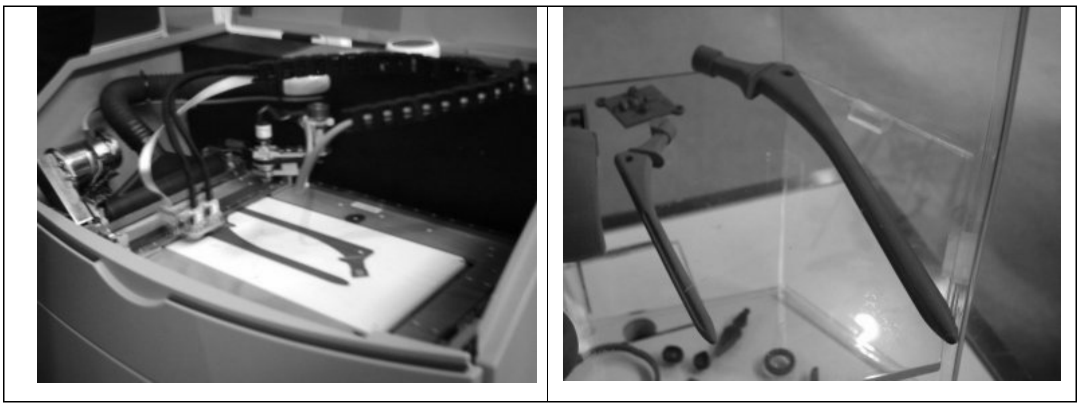


Figure 2. Unimatic FDM machine creating hip replacement 'pattern' parts

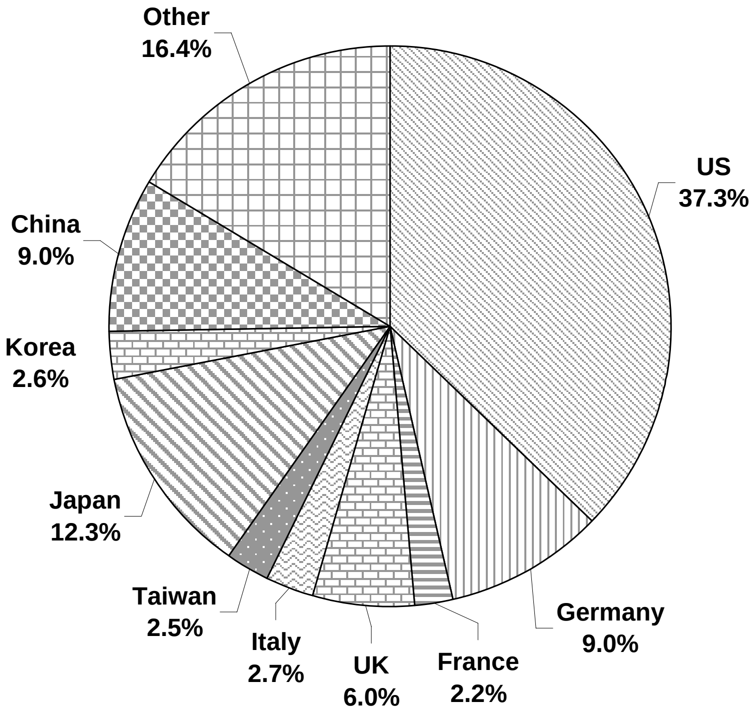


Figure 3 – Installed RP Systems Worldwide 2004 (Wohlers, 2004)

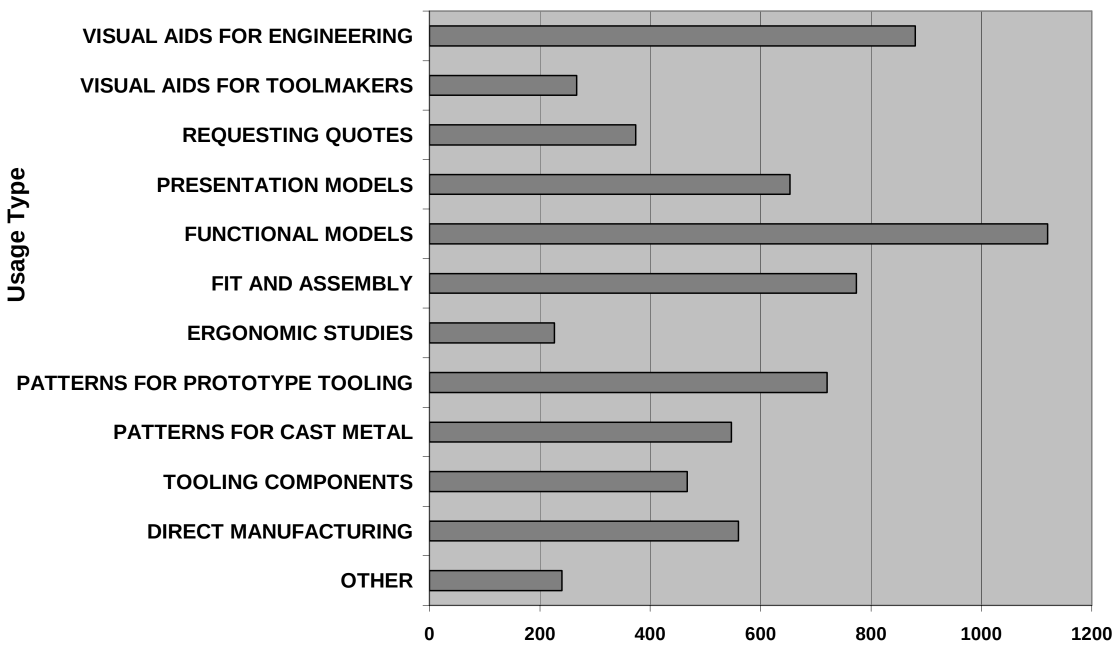


Figure 4 – Typical uses to which RP Technology is put (Wohlers, 2004)

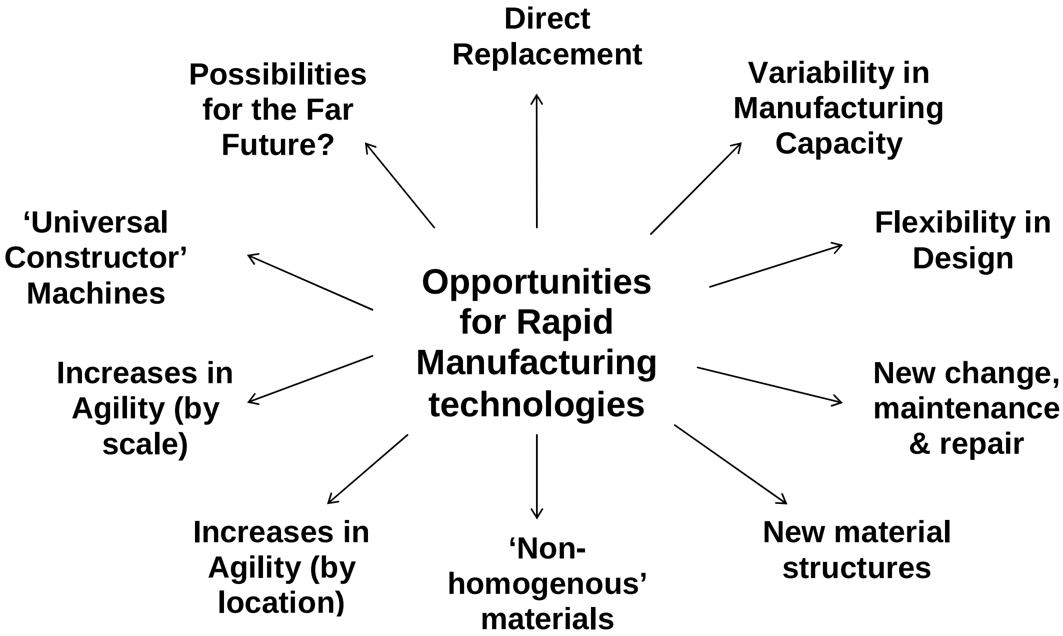


Figure 5. Increasing manufacturing agility using RM methods

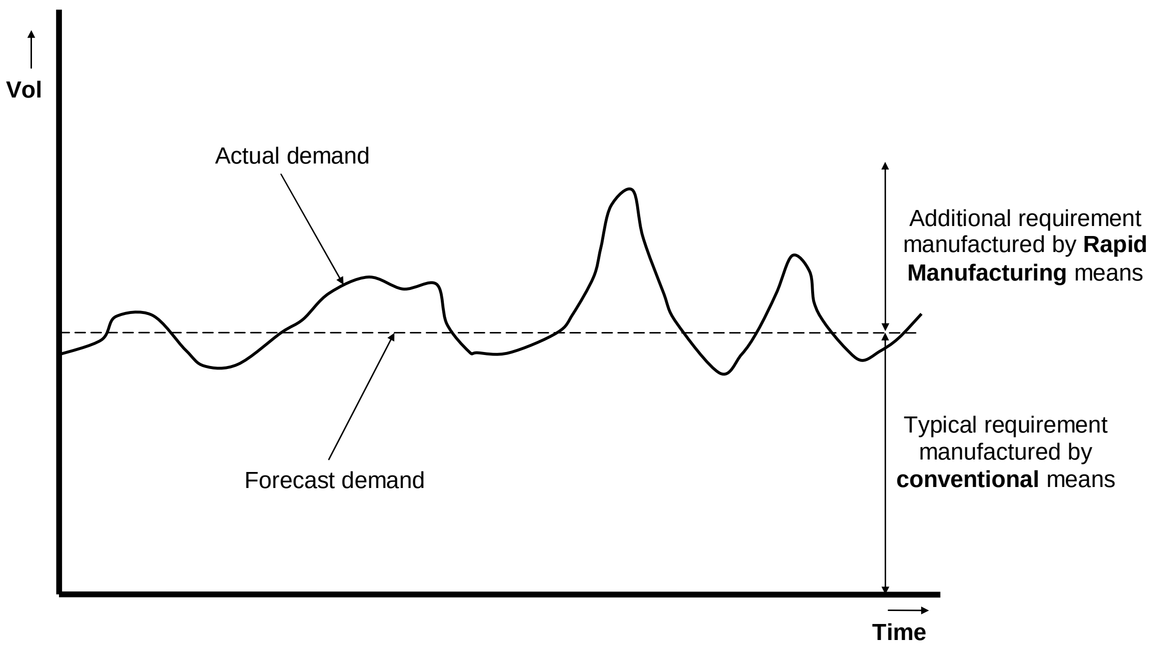


Figure 6. Use of RM to vary manufacturing capacity

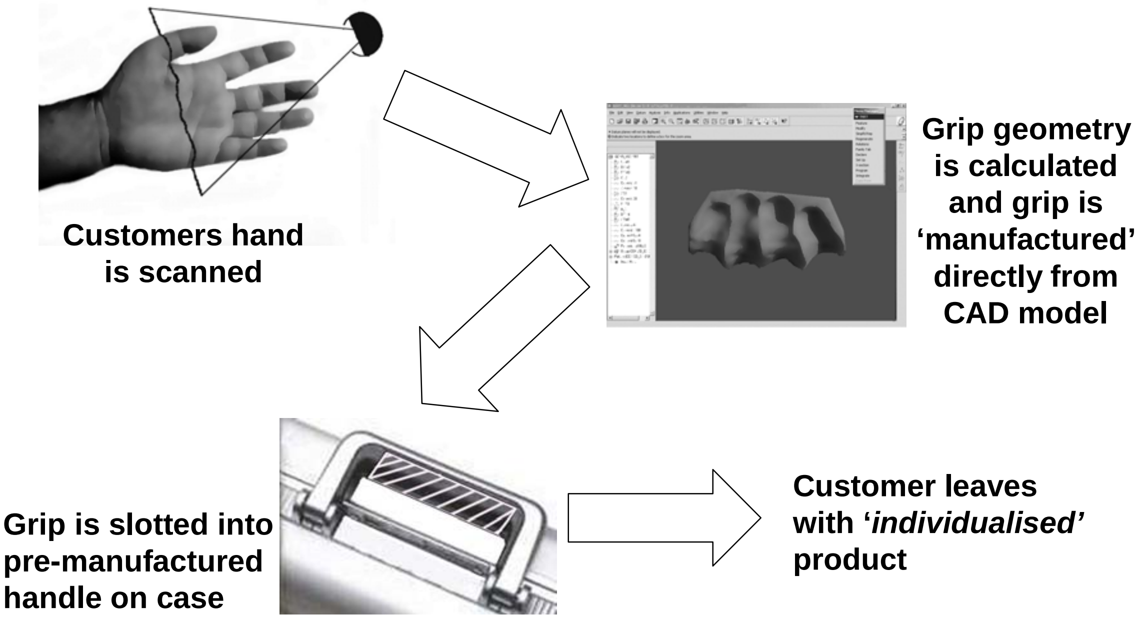


Figure 7. Customization of a consumer product [Bateman & Cheng, 2002]

Figure 8. F1 Suspension bracket directly manufactured by LENS process

(Image courtesy of TCT)

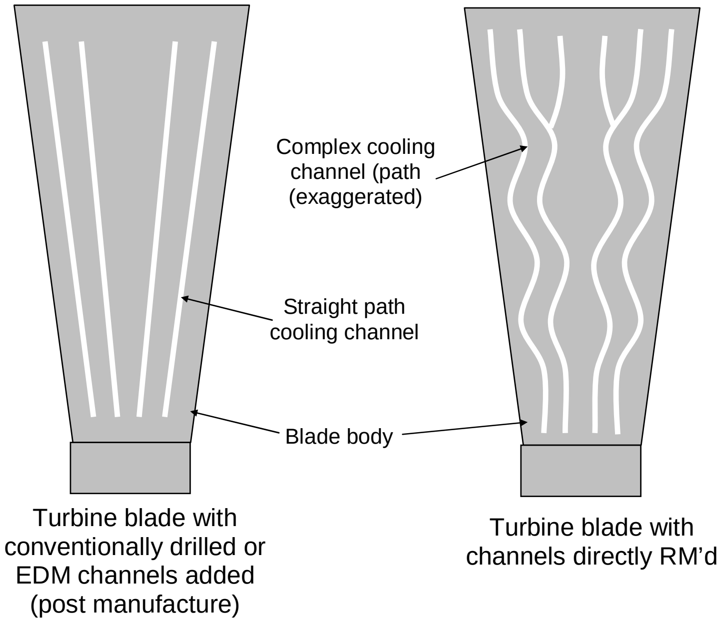


Figure 9. Conventional and RM manufactured turbine blades

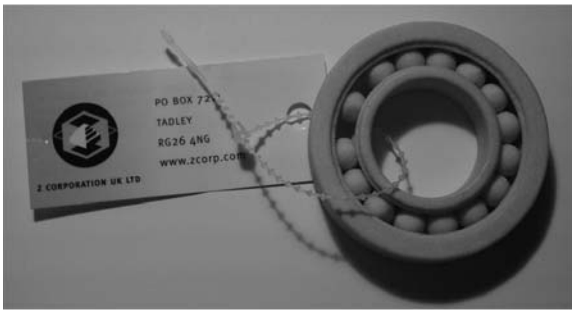


Figure 10. Example 'working' bearing – produced by Z Corporation

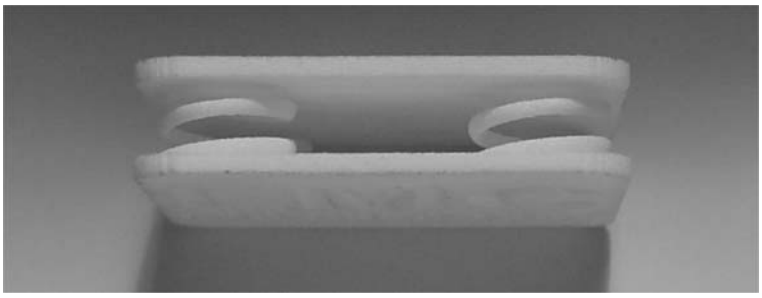


Figure 11. Product created with internal springing (single material)

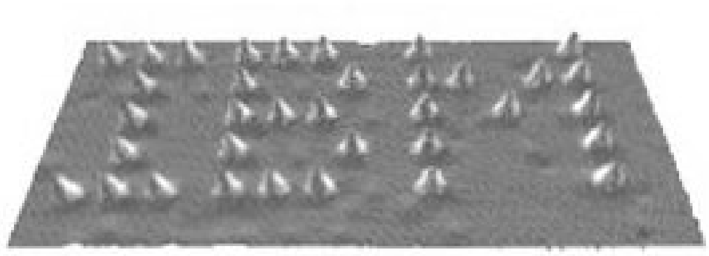
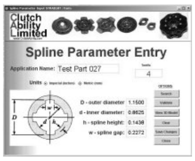
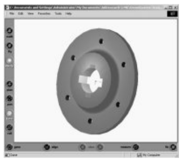


Figure 12. IBM logo built from 35 individual atoms (image courtesy of IBM Research)

(a) CAL system menu



(b) Parameter input

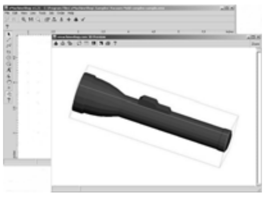


(c) Modified CAD model

(d) Finished Product

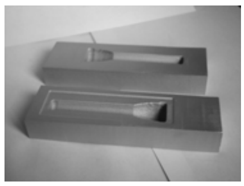
Figure 13. The ClutchAbility RM Scenario

(a) wydiwyg home page



(b) Completed design

(c) Sending to outlet



(d) Completed moulds

Figure 14. The wydiwyg.co.uk RM scenario

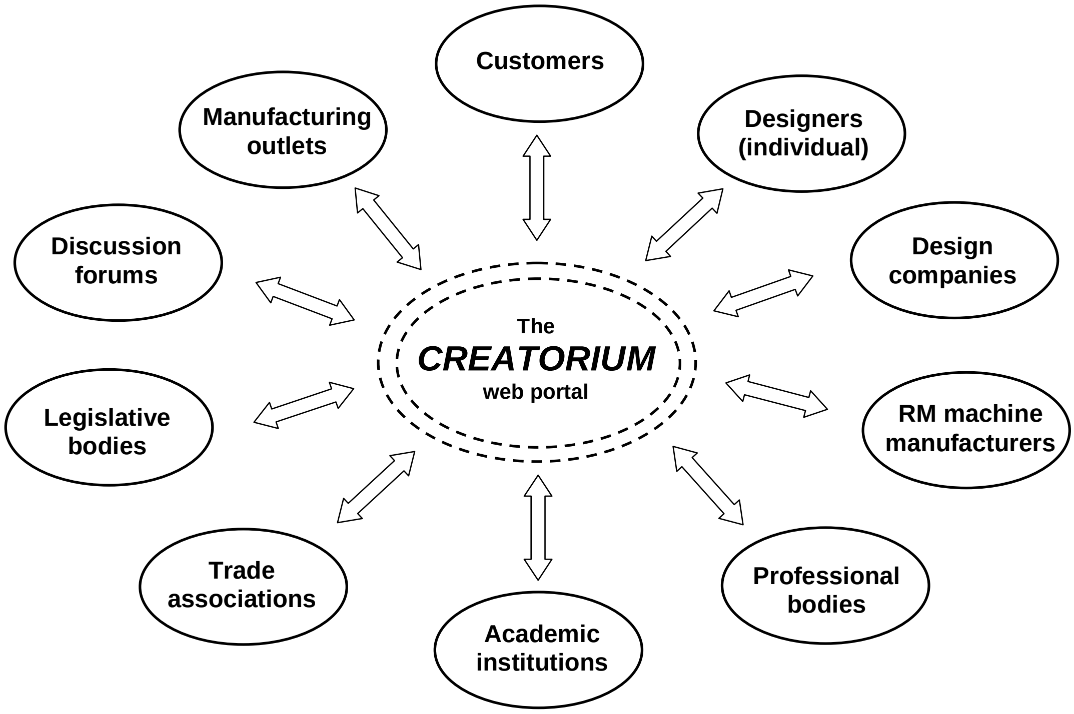


Figure 15. Stakeholders in the Creatorium web portal