Manufacturing Reinvented
additive manufacture and a second industrial revolution

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A one-day MADE[1] conference on the design, business and societal implications of Rapid Manufacturing; part of the London Design Festival 2007 and Innovation at the RCA 2007

Report by Hugh Aldersey-Williams

Rapid Manufacturing – the making of complete objects by additive or layering processes from digital 3D form data – will reshape the century. It may change everything about our products – the way they are made, the way they are designed, and our relation to them as users and consumers. But beyond this, rapid manufacturing (RM) is a 'radical and disruptive technology with the potential to transform both the global economy and consumer society', according to designer Geoff Hollington, the conference chairman and MADE design mentor.

What is RM?

Richard Hague of the Rapid Manufacturing Research Group, a 45-strong team at Loughborough University, candidly admits that 'rapid manufacturing' may not be the best term, although it is fast becoming the standard. He prefers the term 'additive manufacturing' or the more widely understood '3D printing'. All these labels embrace a number of techniques, including selective laser sintering, where special plastic or, increasingly, metal powder is fused to form solid objects, and stereolithography where an object is created from within a container of liquid resin by scanning portions of it so that it sets.

Making things in this way immediately changes many of the rules of the game. Because forms are not limited by tooling or traditional processes, anything that you can imagine or model on a computer screen can be made. RM promises 'complexity for free', making it a 'manufacturing nirvana', said Hague. This freedom quickly suggests new product opportunities. The most obvious potential is to create customised one-off products for example where a close fit to the body is required. But the fact that products are effectively grown rather than carved out or assembled from parts gives new licence to draw design inspiration from nature. In particular, RM provides the means to do as nature does and optimise designs so that they 'grow' in the most efficient way, using the minimum raw material. This too comes for free in a way, since the basic performance parameters of the object to be made – the size of a chair and the load it must bear, for example – can be used as the data to generate the design. Further off, RM promises great things when applied not only at the macro scale but at micro and nano levels, and if progress can be made towards 'functionally graded' materials which combine different properties within one continuous piece.

Richard Hague

Janne Kyttänen

Naomi Kaempfer

Julian Vincent

Signs and wonders

Exciting examples of the kind of objects that can be made already came from the Dutch design company Freedom of Creation and the Belgian company Materialise.MGX. Janne Kyttänen of Freedom of Creation has been hailed as the most influential designer working with RM today. His designs include lampshades with the intricacy of flowers and even an RM handbag . Kyttänen began looking into RM technology when he realised that 'the way the planet was arranged was not really efficient'. Money, music, words and images can be exchanged virtually – shouldn't it be the same for products? If it were, it could bring environmental rewards in reduced use and transport of materials and products and social benefits such as reducing the pressure to use for child labour.

This is the ideal. The reality for now often seems to involve making giftware and packaging. Freedom of Creation's projects include cosmetics packs and museum goodies. Yet even these projects hint at the transformed design landscape. 'What is the future of design classics?' mused Kyttänen. 'I think there won't be any. Everyday there will be a different design.' The professional designer meanwhile can expect to work more closely with product users. Designers will go 'from gods to guides'.

Naomi Kaempfer of Materialise.mgx has commissioned leading designers to create a wide variety of RM objects. Like Freedom of Creation, the company has found lighting products to be suitable subjects for experiment. They combine highly decorative or sculptural form with the convenient quality that they are seldom touched. Both suit the special plastics required by RM today.

Kaempfer wished to consider what was needed for RM to achieve critical mass – to reach the point where it moves from being an avant garde plaything to a manufacturing norm. 'When does the novelty become old news?' In some ways, she thinks, that point is already being reached as people have realised that rapid prototyping (RP) was merely the harbinger of something greater – making finished products. But other shifts will have to take place: towards stronger, more versatile raw material, faster, cheaper RM machines, and greater recyclability.

Inspired by nature

While commercial designers push to find ways in which RM can be exploited to make contemporary products, others are looking into the more distant future. For them nature inspires not merely the form of objects but the whole paradigm by which they are made. **Julian Vincent,** professor

[1] Manufacturing Reinvented was the third annual conference of MADE, hosted by InnovationRCA at the Royal College of Art and organised in association with MADE design mentor Geoff Hollington.
MADE is part of the Materials Knowledge Transfer Network (KTN) funded by the UK Government, forging a link between designers and other sectors of the KTN concerned with metals, plastics, textiles and the full range of modern materials.
The core partners of MADE are the Institute of Materials, Minerals and Mining (IOM3), the Royal College of Art (RCA), the Design Council, the Institution of Engineering Designers (IED) and the Engineering Employers Federation (EEF South).
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of biomimetics at Bath University, displayed charts such as a plot of Young's modulus versus density for a range of materials to demonstrate how natural materials are often better optimised than our metals and plastics. Nature gets by, Vincent explained, with a couple of basic polymeric materials and two ceramic fillers arranged in a huge variety of different composites, whereas our technology has 300 distinct materials. Among them, only engineering ceramics push the envelope beyond natural materials' performance levels. Furthermore, natural materials come with recyclability as a given and often have the ability to repair themselves. In short, 'life is responsive, engineering isn't.'

One practical example of how to make engineering more responsive came in the form of RepRap, a first stab at a machine that can manufacture its own successor. This is the creation of **Adrian Bowyer,** a lecturer in engineering at Bath. Bowyer used a fused deposition modelling rapid prototyping machine as his starting point. The initial challenge was to get the machine to be able to make the most crucial component, the write-head. This was achieved except for various nuts and bolts and a small electric motor (the engineers allowed themselves to cheat with parts that were universally available and cheap). Joints for the Cartesian frame within which the write-head operates were also successfully made by this RM technique. So far, so good.

Where this goes next illustrates some of the awkward questions that RM poses regarding traditional notions of manufacturing and intellectual property. Bowyer would propose to make it open-source so that everybody could access the technology. After all, 'you'd only sell one anyway if it makes itself'.

Exponential growth

A machine that merely replicates itself and nothing else would serve little purpose. So now, what if such a machine not only made its own replacement, but made something else as well, say a comb? The true potential of this idea becomes apparent. Say you can make 10,000 combs a day by an injection moulding process. If the RepRap makes just one comb in that time, it seems hopelessly uncompetitive at first. But on day two, there are three combs, on day three seven combs and so on. RepRap and its progeny surpass the injection moulding machine in productivity on day 19. Like most growth in nature, the rate of growth is limited only by the supply of raw material. The cost of the first replicant may be astronomic but it quickly becomes insignificant as the cost

Delegates were invited to record their thoughts and comments during the conference

'I love the idea of complexity for free and shape optimisation – putting material only where it is needed.'

'Almost seems like a race to see how many products you can produce in a year. Where's the time for editing or reflection?'

'What about the ethical dimension? How does this fit with making luxury packaging?'

'Excellent. Finally, somebody acknowledges consumers don't like long-lasting products and we can exploit this by designing fast and making faster.'

'Amazing. The end of exclusivity. Anyone can be a designer now.'

'Is this an open door to produce even more stuff to use once and throw away?'

'Recycling hasn't been mentioned so far. Maybe the machine has to absorb all its failed test results.'

'The self-replicating machine can bring manufacturing to even the poorest people.'

'What about the potential for RM to produce parts to repair products?'

'Why has the human race become so obsessed with validation. Isn't evolution a validation process too?'

'I've spent years trying to optimise materials. Are we now going to compromise materials?'

'What about materials' emotional as well as functional and structural qualities?'

Adrian Bowyer

Chris Sutcliffe

Phil Reeves

Max Comfort

of its successors tends to the cost of the raw material and energy used alone.

Other things will happen that also follow the analogy from nature. 'Evolution kicks in,' Bowyer explained. If it is open-source, people will improve the 'genotype' – the CAD data that contains the information to make the RepRap. Old machines will make replacements with improvements in a machine equivalent of speciation.

The challenge for engineers, designers and materials scientists is to understand how thoroughly RM remodels the human conception of manufacturing. At the moment, said Vincent, 'we're not using the power of the system to reposition objects. We're just making them by computer control.' The challenge is to see that the technology can offer new, more subtle solutions to problems we've only solved in the crudest way in the past. This will require us to rethink the way we frame our design problems. At the moment, we incorporate a particular function by fastening on a discrete set of parts designed for that function. 'Human engineering tends to solve problems by changing the global conditions.' If you want a tape player that also records, for example, then you build in a microphone. Nature works differently. An insect carapace, for example, uses local variation in its material properties to incorporate sensory function, such as sound detection.

But 'if we are to grow products, what design language is appropriate?' asked **Geoff Hollington**. He showed examples of natural 'soft-bodied locomotion' that do things we presently do with wheels, gears and levers. Yet picking something up, for example, could be accomplished not by a grapple but by something more supple like an elephant's trunk. If we emulate nature in this way, are designers necessary at all? Yes. Their job will be to 'design how nature designs, not what nature designs.' In future, people will sell not the products themselves merely the information needed to grow them. Natural algorithms could be taken further, enabling products to sustain and repair themselves in use too. By way of example, Hollington showed a concept for a pen whose nib would not become blunt because it drew 'nutrients' from its own ink just as our teeth take calcium from our food.

Reality check

It fell to **Chris Sutcliffe** of the University of Liverpool Manufacturing Science and Engineering Research Centre to bring the audience down to earth. The much vaunted advantages of RM were also mostly its drawbacks, he observed. Design freedom is all very well, but for unqualified designers? Customisation is fine, but so far there's only a small market for customised items. The environmental promise of reduced waste is hardly realised at the moment when RM machines must use specialist, sometimes toxic material that cannot be recycled. What's more, today's RM machines are expensive to buy and run, largely incompatible with conventional manufacturing, hard to use and maintain, and only rapid in theory.

But despite these misgivings, Sutcliffe remained positive. 'I have a good feeling now about manufacturing in this country and RM is a big part of that future.' The immediate task is to improve RM in day-to-day operation. 'The challenge is to produce a fully scaled, verified, validated and useful manufacturing process,' said Sutcliffe. At the moment, 'most users don't know what validation means'.

For Richard Hague, there were problems even before you get to making things. The design possibilities are unreasonably restricted by the CAD tools available which themselves have been designed with conventional manufacturing constraints in mind. CAD is 'virtually useless' for designing RM objects being neither fast enough nor able to handle many of the forms and details that RM makes

Geoff Hollington (left) chairing a discussion panel at Manufacturing Reinvented

possible in principle. Even an object as conceptually simple as a Klein bottle (the 3D equivalent of a Möbius strip, a vessel whose inside and outside are part of the same single surface) cannot be modelled by CAD, but it can easily be made by RM. The same goes for body-fitting products from hearing-aids to sportswear matched to individual users' bodies.

Given these obstacles, it is perhaps surprising that RM products are already widely available. **Phil Reeves** of Econolyst, an RM consulting firm, presented the scenario – a somewhat exceptional one admittedly – of a professional footballer's family. In 2007, they have RM furniture and light fittings in their home. Some building components are also made this way too. They benefit from (expensive) custom dentistry and hearing aids. In five years' time, they will acquire more customised designs in their lives, from car steering wheels to hip implants, and golf clubs to school rucksacks that sit comfortably on your back. They will have at home one of the first consumer 3D printers which the kids use to make souvenir computer game avatars. In another five years, by 2017, more invasive RM technology may be able to make intricate biocompatible parts to repair the liver of our ageing and increasingly dissolute soccer star.

Consequences

These exciting visions of the future were tempered by a sense that there would also be unforeseen consequences from such a revolutionary technological shift. Geoff Hollington felt that we were emerging from the period of consumerism into a new era. 'Several speakers commented on the market demand for constant novelty,' he noted. But 'how does that relate to our need for greater environmental sustainability?' Would there be any professional role left for designers in the future? What should be the priorities for materials science and engineering? What happens to matters such as product liability if people are making things in their own homes?

Some difficulties may be more imagined than real. Conventional notions of validation disappear if some 'evolutionary' mechanism takes care of the product's 'fitness', for example. As for product liability, maybe an appropriate analogy is with domestic cooking where the edibility of the result is down to the cook but the quality of the ingredients is down to the supplier.

Again, it is useful to bear in mind nature's model. The present need for manufactured parts to have high tolerances and repeatability arises largely from the requirements of product assembly – not from consumer demand, even though uniformity has become a consumer expectation. 'The point of repeatability disappears if the product is made in a single pass,' observed Vincent. We are prepared to accept (just about) that fruit are not identical when we buy them and expect to pay less for inferior specimens. The same may come to apply to RM products.

Setting the day in the broader context of the need for sustainability, the social entrepreneur **Max Comfort** saw the potential for social transformation. 'There's never been a better time for a major paradigm shift,' he suggested. Comfort foresaw 'a 21st century Arts and Crafts movement' arising based on the democratisation and localisation of design activity using RM, but warned: 'rapid manufacturing must benefit everyone, not just the current culture of exploitation'.

Hugh Aldersey-Williams is a writer and curator in design and science. He was the design critic of the New Statesman for five years before curating the exhibitions 'Zoomorphic' and 'Touch Me' at the Victoria and Albert Museum. His new book, Panicology, a feelgood book about the global disasters we supposedly face, is published by Viking Penguin in February 2008.

Growing Pains: five designers, five RM objects

Manufacturing Reinvented put its money where its mouth is with a pioneering demonstration of the potential of rapid manufacturing technology. We invited five leading designers to design a 'compelling and innovative product that can only be made by an additive rapid manufacturing process'. Here's what they came up with, together with some of their comments on the new design process.

Rock Music: Sebastian Conran, Conran & Partners

Rock-Music is an adaptation of a traditional Pan Pipe. It satisfies an ancient function using contemporary technology. The flute-like instrument functions as a Helmholtz oscillator based on 'closed vessel' acoustics. Conran folded the tubes around to achieve more compactness. 'It's a complex yet simple form. I really cannot think of any way of making this other than RP/M.'

Conran was enthusiastic about not having to worry about constant wall thickness (a constraint with traditional plastics manufacturing to do with the rate of cooling). The design was developed as a virtual CAD model. Had there been an opportunity to make a prototype (which there wasn't due to the time constraint of the competition), Conran would *have* used this to refine the tone of the instrument. 'The absolute wonder of this technique is that it allows you to constantly evolve and refine.'

Rock Music

DOPI: Gareth Jones, The Product Works

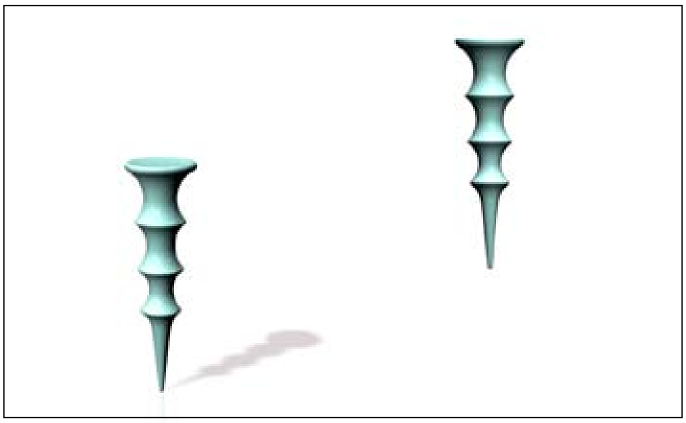
Dopi amplifies the sound from an iPod earpiece using an exponential horn wrapped into an involute. 'We thought the name Dopi (ipod backwards!) which we thought suited its biomorphic nature.' Such as object could be designed to be assembled from different parts, but this would impair its acoustic performance.

The geometry is the product of a simple mathematical formula, but not one suited to the Cartesian world of CAD. 'The limiting factor proved to be the software. Because it is based on subtractive technology, it struggled to model the natural organic shapes we wanted. Richard Hague said this would become a problem as manufacturing constraints are lifted, and I can see now what he meant!'

Dopi

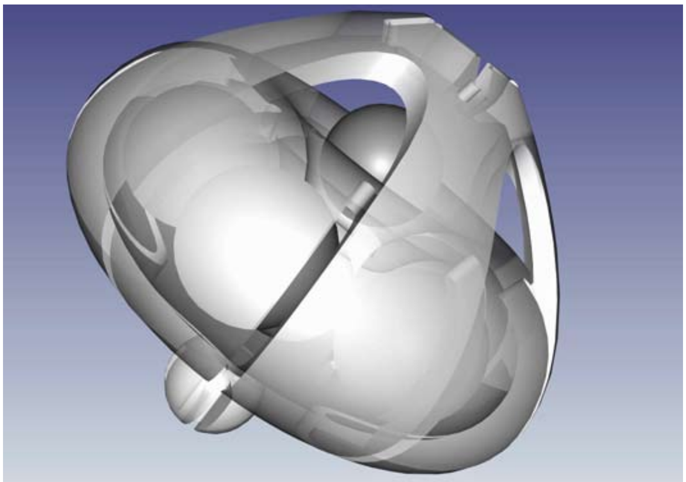
Psycho, Robin Levien, Studio Levien

Psycho is a handheld device for piercing the plastic packaging around prepared foods. Each one is customised to fit the hand of one user. Levien began not with sketches or even a product concept, but a lump of non-setting clay which he manipulated until the idea of an object based on a squeezed



Psycho

Spuzzle



Make & Shake

hand shape came to him. This rough model was then copied into CAD form for transfer to the RM machine.

Psycho is a satirical comment on our hurried lives. 'The average time to prepare a meal in the UK is 10 minutes, how long before this is the only kitchen gadget that we will need?' Levien purpo sely avoided creating an object that could only be made by RM – Psycho could easily be lathed – feeling that RM would ultimately be used to make quite ordinary things. 'At the beginning of a new technology, you're thinking how to fully exploit it. But just because you can do something doesn't mean you should.'

Spuzzle, Dick Powell, Seymour Powell

Spuzzle is an intriguing puzzle – the challenge is to tease out the small sphere that lies at the centre of a number of loosely nested concentric spherical shells so that it emerges from a hole in the outermost sphere. For Powell, the Spuzzle was a chance to realise RM's potential 'to mould the unmouldable'. Even though it comprises several discrete parts that have no connection, it would be topologically impossible to assemble this object from those parts because of their sizes.

The idea went from a verbal phrase to a sketch to 3D CAD before it was transferred to the RM machine. A prototype stage would have allowed the designers to refine the Spuzzle's internal dimensions to create a working version.

Make & Shake, Marek Reichmann, Aston Martin Lagonda

Aston Martin designers first tried to think of an item relevant to the automotive industry, but were unable to do so – revealing perhaps how much existing car components are presently biased in their design to be manufacturable by conventional means. 'We were trying to look for something aspirational that would be impossible to manufacture in another way,' said Aston Martin's Nick Kent.

Instead, they came up with Make & Shake, a modular rattle-type musical instrument. Each module comprises a cage with a ball trapped in it. The modules can be coupled together to make a chain similar to a tambourine. Design proceeded just as for a conventional product, with concepts sketched on paper and then worked up in CAD. But the final object was made direct from this file without concept models or prototypes.

The 'factory' view, Martin Watmough, RapidformRCA

The designers used rapid manufacturing equipment provided by RapidformRCA at the the Royal College of Art and by the Rapid Manufacturing Research Group, Loughborough University. RapidformRCA manager Martin Watmough worked with the designers to develop the brief that would allow them to explore the full potential of the technology while also remaining within its very real constraints at present. Watmough was on hand to guide the designers as necessary, though he found that his tutoring mostly involved reminding them of the brief. Watmough found different things to praise in the various design concepts, ranging from their embrace of the possibilities of customisation to their imagination in the face of severe technical challenges.The process was a learning exercise not only for the designers but also for Watmough. For him, one major realisation was to see that 'you still need design verification and a prototyping phase' – traditional aspects of any conventional design cycle that were sacrificed due to the compressed competition timeframe. A future study might set designers the task of developing a more thoroughly worked out concept for rapid manufacture.

Manufacturing Reinvented delegates examining the five designers' rapid manufactured products

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