BEYOND PRE-FABRICATION - THE POTENTIAL OF NEXT GENERATION TECHNOLOGIES TO MAKE A STEP CHANGE IN CONSTRUCTION MANUFACTURING

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ABSTRACT

This paper describes a number of next generation manufacturing technologies which may find applications in construction such as digital fabrication and rapid prototyping. It will also look at some of the work being undertaken within UK Government funded research projects within the overarching area of Freeform Construction. In addition to explaining the technical processes and products of these, the paper will explore the delivery management issues and theorise how these next generation technologies have the potential drive lean thinking deep into the heart of the construction industry. The technology and delivery issues will be presented in a conceptual model of construction manufacturing.

The underlying premise for this research agenda is the static nature of construction – with the basic logic behind the processes being unchanged for centuries, construction is probably the last bastion standing against technological revolution. Next generation manufacturing technologies have the potential to drive the paradigm shift needed to achieve the changes the industry is being pushed towards.

This paper provides a view of a different construction industry for the coming century and shows the processes that may help shape it along the way.

KEYWORDS

Construction manufacturing; freeform construction, digital fabrication, rapid prototyping, automation.

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INTRODUCTION

The construction industry of today has changed little in essence from that of half a century ago, that is labour intensive, site based, constrained by the prevailing weather and the standard approach of forming the outer shell with a subsequent internal fit out. The most notable change perhaps has been advancing technology altering the skill base of the trade operatives and increasing their number as buildings have become larger with a greater variety of materials and components but an operative from 1506 would still recognise the site as a place of building construction. Would that be the case in brewing for example, or modern food or clothing production? So it is probably fair to say the industry is due a revolution.

Moving part or all of the building work into a factory environment enables a radically different industry to emerge – so different that it is often viewed as manufacturing rather than construction even though the output is an integral part of construction project delivery. The changes enabled by factory working vary from re-engineered products (Pasquire & Connolly 2002) as demonstrated in the case of pipe modules below (large photo showing the re-engineered factory designed module, inset the original project design)

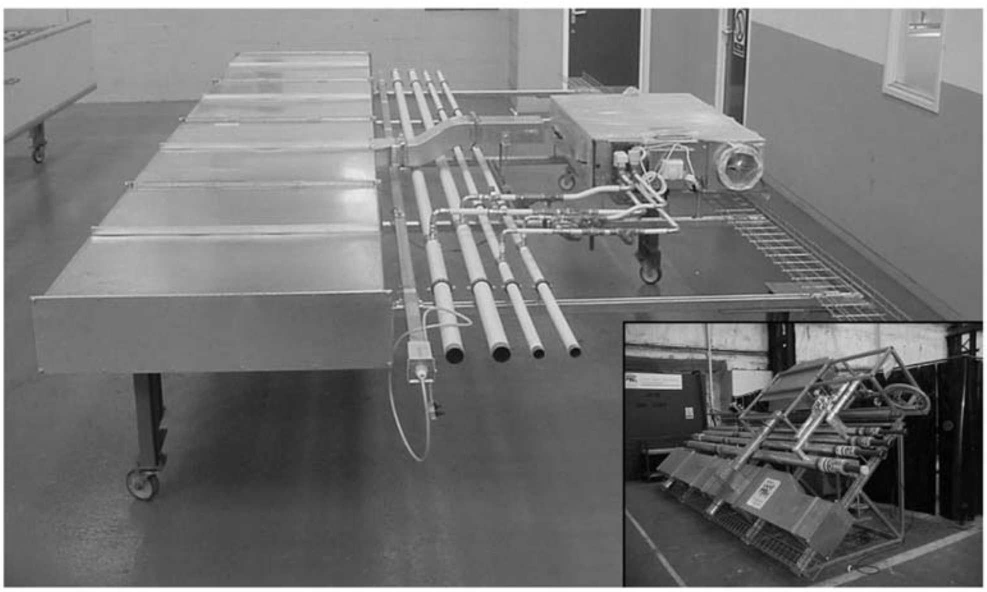

Figure 1: Pipe module. Photo courtesy Crown House Technology

This re-engineering is a result of the changed manufacturing processes available and the opportunity to design for manufacture and assembly (DFMA). The factory environment removes the constraints of traditional construction logic allowing assembly from top down and/or inside out, with every activity being carried out at a safe working height. Offsite construction or pre-fabrication however is only suitable for certain projects and clear drivers and constraints for its use have been identified (Gibb & Isack, 2003) and the cost and value benefits defined (Pasquire & Gibb, 2002; Pasquire et al 2004). The market share of offsite construction in the UK was assessed as 2% in 2004 (Goodier & Gibb 2005). Although an ambitious target of doubling this by 2010 has been set by the Buildoffsite[4] initiative, the offsite market share will still be minimal. Despite recent advances in manufacturing technologies offering a number of current and potential applications that may totally reform the industry current offsite construction still uses existing technologies.

Manufacturing design makes wide use of computer aided 3D solid modelling (CAM) which provides digital visualisation and simulation.

MANUFACTURING TECHNOLOGIES

The underpinning manufacturing technologies involve one, or a combination of, three basic approaches additive, formative and subtractive. Construction also uses these three approaches for varying aspects of the building works although overall the construction process are defined by Burns (1998) as additive:

- Additive – describes the process of adding material to build up the product, in construction this would be laying bricks, installing partitions, applying finishes etc
- Formative – describes the process of forming the product through the use of moulds. In construction this would encompass all in-situ concrete work
- Subtractive – describes the process of forming the product by removing material through cutting, milling or grinding - for example cutting to size of stone, timber, sheet metals etc.

A revolution in manufacturing, driven in part by the transformation within post war Japan and the advent of lean thinking, has led to a new generation of technology increasing the automation of processes and underpinned by advanced IT or digital fabrication. One family within these technologies is collectively known as Rapid Prototyping [termed Solid Freeform Fabrication in the US] [conceived in Japan and US at the same time, Kodama and Hull]. All current Rapid Prototyping processes work by adding layers of material to build up three-dimensional objects – hence the term additive. It is the belief of many people that this Rapid Prototyping technology will eventually move into the heart of the manufacturing process and end use parts will be made directly by these techniques. This area has become known as Rapid Manufacturing or Additive Manufacturing Technologies.

Research performed by the Rapid Manufacturing Research Group[5] has included Rapid Tooling - using Rapid Prototyping processes to directly manufacture tooling for processes such as injection moulding and die-casting. More recently, research has been focused in the area of Rapid Manufacturing – initially seeking to use Rapid Prototyping processes to manufacture end use parts but ultimately requiring new processes themselves. The group has already shown that it is economically feasible to use the existing commercial Rapid Prototyping systems to manufacture parts in quantities up to 20,000 (Hopkinson et al 2005, Buswell et al 2005) To differentiate, the process is called **Rapid Manufacturing** if the product is put to direct end use, **Rapid prototyping** if the product is used for conceptualisation, testing, analysis

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[4] Industry led initiative funded by the UK Department of Trade and Industry
[5] http://www.lboro.ac.uk/departments/mm/research/rapid-manufacturing/index.html

but not as an end product. **Rapid tooling** is when the product is used for tools and moulds or as a pattern from which a tool can be formed for the further manufacture of the end product.

RAPID PROTOTYPING TECHNIQUES

According to Noorani (2006), rapid prototyping has a five step process:

1. Creation of a CAD solid model.
2. Conversion to stereolithography (STL) file
3. Validate and repair the model and slice into 2D cross-sectional layers (rapid processing)
4. Make or "grow" the prototype or part
5. Part removal and cleaning, postcuring and finishing (post processing)

The first step in the process CAD (computer aided design), is the visual design and representation of objects, buildings or systems on computers for visualisation, analysis, manufacture or construction. Steps 2 and 3 form part of computer aided manufacturing CAM, a system of analysing and interpreting CAD information for consequent manufacture or construction. There are many techniques which exist and are emerging but these are commonly classified into six basic techniques available for step 4, making the part or prototype (Noorani 2006), these are:

- Stereolithography (SL or SLA) – uses photosensitive resin cured by laser
- Laser Sintering/Fusion (LS or SLS) – applying an IR laser to melt or sinter a powder based material
- Fused Deposition Modelling (FDM) – generates 3D models using extrusion
- Laminate Manufacture (LM or LOM) – Trims or cuts sheet materials to correct size which are stacked and bonded into a solid block
- Jetting (MJM) – Inkjet printer arrays apply polymeric materials where required
- 3D Printing (3DP) – uses ink jet printing heads to deposit binders onto powders to build up the part.

Rapid Prototyping gives a fully automated process which uses computers for the design of virtual models, the control of systems and machines and the construction or manufacture of parts, in other words a digital method of fabrication. It currently finds a use within the construction industry as a modelling tool to assist in project visualisation with some rudimentary structural testing. Construction and architecture are also embracing Rapid Tooling as a means to derive moulds and tools using High Speed Machining (HSM) to form freeform moulds into which building components are cast or formed. But the technology also gives us complete freedom of geometry – enabling the production of freeform and fully optimised parts. Digital fabrication and freeform geometries are the focus of a new research group at Loughborough University. Combining the expertise from Construction Management[6] with Rapid

[6] http://www.lboro.ac.uk/departments/cv/research/groups/built_env/con_man/index.html

Manufacturing within the Innovative Manufacturing and Construction Research Centre (IMCRC) at Loughborough University, UK has given rise to the Freeform Construction Group[7] which is exploring the feasibility of using Rapid Prototyping systems within the construction industry now and in the future in what it calls "freeform construction".

FREEFORM CONSTRUCTION

The group has defined this as "a truly adventurous and far-reaching new construction method which will change the very future of building and construction as we know it. It will revolutionise the way we build, it will enhance existing construction processes and bring about new capabilities for the construction process, and it will allow us to build in ways which simply weren't possible before. Freeform Construction is about 'printing' buildings, as if you were printing this page. It's about combining the whole design, construction and maintenance process into a seamless operation to produce structures and components which meet the challenges of our changing world and which will allow us to build on any terrain, against any backdrop, anywhere on the Earth, the Moon or Mars."

The use of Rapid Prototyping technology in Freeform Construction has many implications for the construction industry

- It is an automated and 'lights out' 24/7 process
- The reliance on IT demands numerical precision
- The reliance on diminishing skilled trades is reduced
- Manual intervention is significantly reduced
- 'Design before build' demanded
- Complete geometric freedom for complex internal and external detail
- Full integration of services and complex internal structures
- Higher degrees of structural optimisation provided
- New construction materials and processes will be developed
- Solutions for waste, recycling and energy conservation will be provided by utilising mineral and pastes over timber and steel.
- Single materials and quasi-composite structures (compositions which mimic behaviour of multiple materials)
- Deployable solutions for arid, hazardous or hostile environments become available.
- Embraces both automated 'wet' and 'dry' construction practices simultaneously

Although the Rapid Prototyping technology offers many attractive features, there are some limitations to its potential. Firstly, the name Rapid is misleading as it can not compete with mass production in terms of speed for high volume but it is effective for low volume, high cost

[7] www.freeformconstruction.co.uk

customised products. The technology offers added value but may not be cheaper compared to traditional methods and has only a limited range of available materials at present. It is also true to say that in some instances quality may be reduced with less precision/resolution. However, research projects being undertaken by the FreeForm Construction Research Group at Loughborough have already delivered a number of milestone findings and prototypes that suggest this technology does indeed offer important opportunities to construction. These include:

1. The proposed processes are capable of fabricating modular panels and freeform beam sections with enhanced functionality. Figure 2 below shows a section through a prototype panel constructed in resin demonstrating the potential value adding features of building walls using freeform construction (FC).

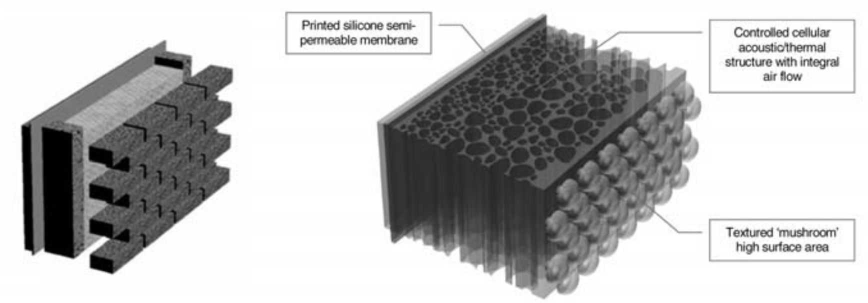

Figure 2. Wall Panels

The FC panel (B) is formed in a single operation and the fabric is seamless. This means there are no interface issues unlike the conventional wall (A) where several operations are needed and interfaces exist between trades and materials. In this example, the intention was to replicate the conventional wall panel. To maximise the opportunities of the technology, it is more useful to design a new wall structure based on functional requirements rather than imitating traditional approaches.

2. Structural optimisation can easily be achie ved using a single material.

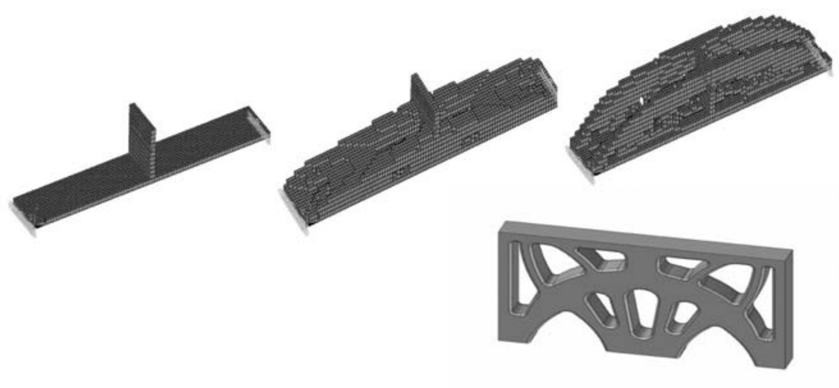

Figure 3. Structural Optimisation

The computer generated images in Figure 3 above show how freeform techniques can produce enhanced limit state designs for structural purposes. A beam is designed and built up layer by layer as a load is applied, the resultant structure gives maximum strength with minimum material. Although these designs can be produced as small scale prototypes, limitations in material performance mean scaling up for structural elements within buildings is not currently feasible.

3. Advanced acoustic properties; panels formed from gypsum based material act as resonator structures. Figure 4 below shows how the technology permits the formation of continuous, complex voiding within a solid panel structure without joints and seams.

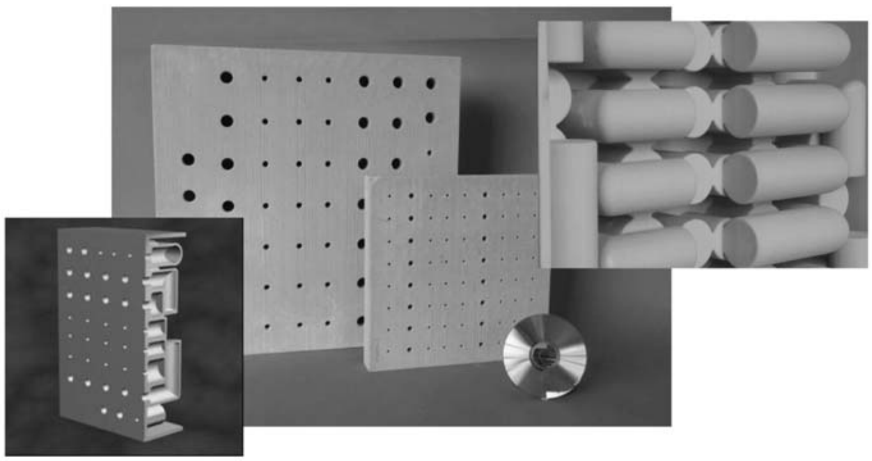

Figure 4: Resonator panels "printed" in 3D gypsum based material (reproduced with kind permission of O. Godbold and R. Soar)

4. Optimised thermal properties can be integrated into the wall structure as it is created. This can be infinitely varied depending on the thermal performance required for the specific location. Figure 5 provides an example of variable multi-layered structure for optimal thermal performance.

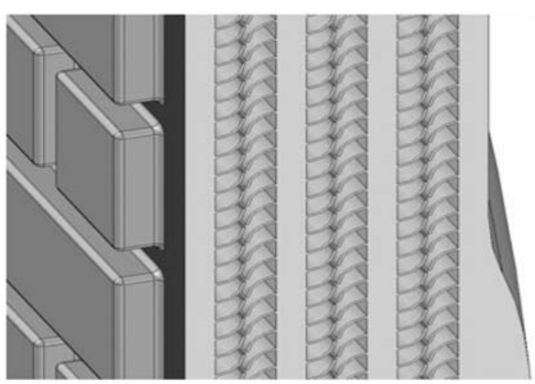

Figure 5: Optimised thermal properties

5. Opportunities offered by reversing the rapid prototyping process exist within architectural features. Reverse Engineering enables production of an object based on data derived from the finished product or its prototype without reliance on the initial method of production.

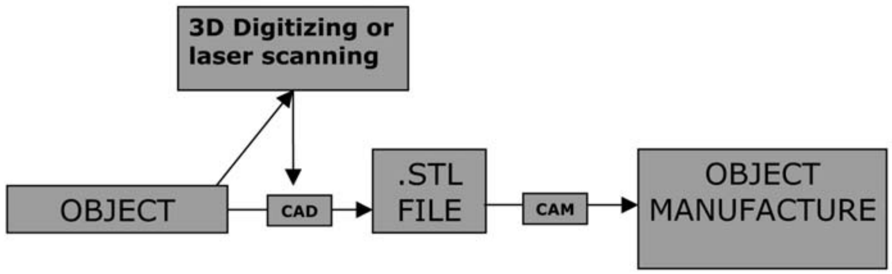

Figure 7 Reverse Engineering Process

This provides direct market applications in repairing and replicating elaborate features that are no longer in production. As part of the ArchiFORM research project, architectural plasterwork parts were directly produced for Troika Architectural Mouldings[8], without the need for moulds. For larger quantities, moulds can be produced using Rapid Prototyping technology omitting the need for time consuming and expensive hand moulding and/or sculpting. An alternative use for this technology has been identified and tested within Cradley Special Bricks[9] who manufacture a range of architectural feature bricks and have a substantial market in replacing worn and decayed feature bricks. The traditional production method requires moulds to be made by hand from the existing bricks which then need to be scaled up to allow for shrinkage of the new bricks during firing. The use of reverse engineering to produce the moulds removes many time consuming activities within this process and the CAD and CAM eliminates errors in the scaling delivering certainty of end product. The mould and prototype brick produced using reverse engineering and rapid tooling technology are shown in Figure 8 below.

The current market applications for plaster and brickwork identified are showing significant early cost benefits but only for low quantity production runs at present due mainly to the initial cost of the current methods for reproducing the component moulds which may involve the employment of a sculptor or artist. A full economic analysis is currently being undertaken as part of the ArchiFORM project.

8 Troika Architectural Mouldings
9 Cradley Special Brick Ltd

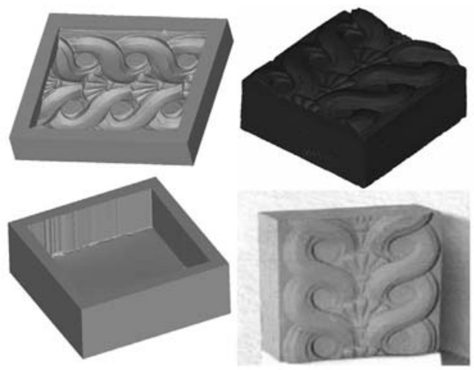

Figure 8: Architectural Brickwork

CONTOUR CRAFTING

Being developed by Professor Behrok Koshnevis of the University of California, USA, contour crafting is an automated construction process using extrusion of cementitious materials. There is an impressive demonstration of the capability of this technology on the contour crafting web site www.contourcrafting.org including Professor Koshnevis's vision of deployability and off-world construction.

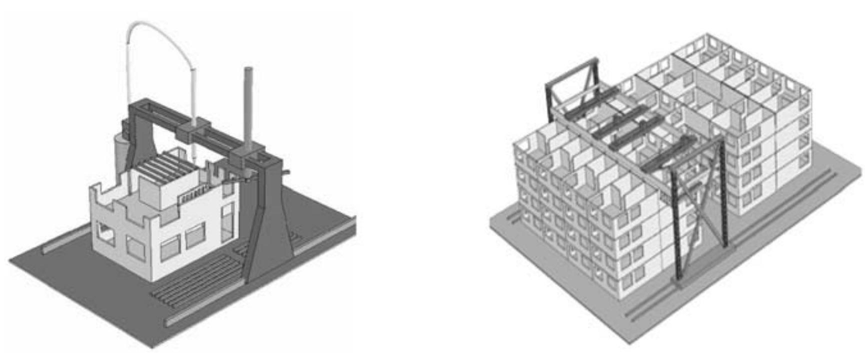

Figure 9. Construction of conventional buildings using Contour Crafting. Behrokh Khoshnevis (www.contourcrafting.org)

DIGITAL CONSTRUCTION

Whether the delivery mechanism is contour crafting, freeform construction or other rapid prototyping technology, the underlying driver is digital capability available through CAD and CAM. This is illustrated in Figure 10 below.

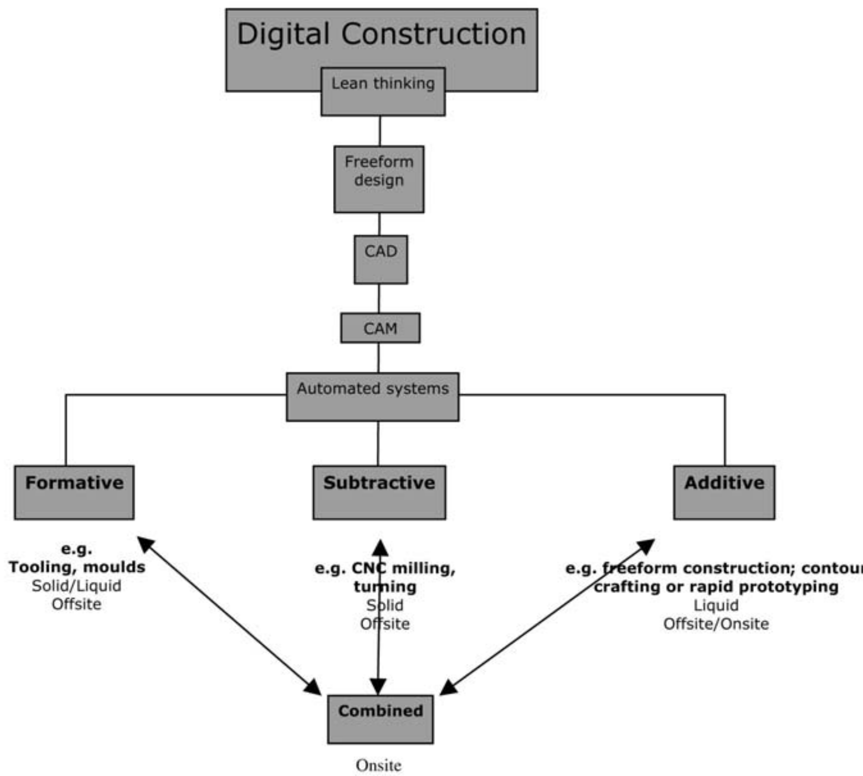

Figure 10: Digital Construction Model

The digital capability offered by CAD and CAM enable extensive automation of processes, automation itself not only removes numerous activities from the process but actually demands a substantially new approach. Being founded in manufacturing theory, digital construction has lean thinking at its heart with all effort focused on design for manufacture (Pasquire & Connolly 2003) making a significant contribution to lean production. When this is added to the responsiveness of the design process to customer demand and the certainty of optimised output, it can be seen that digital construction operates in a lean environment and will form a significant element in Lean Construction and Lean Project Delivery.

The final revolution will come when the technology can match the existing design capability. This challenged was eloquently laid at the door of freeform construction by Holger Kehne[10] at an ArchiFORM project workshop held at Loughborough University, when he presented a number of recent projects in which complex, freeform geometries had been used in the digital designs but lamented that the current methods of construction struggled to deliver these designs satisfactorily. He relished the advent of this technology as he could see its potential to deliver complex geometries in solid materials rather than trying to create at them with sheet materials

[10] Architect, Plasma Studio, London www.plasmastudio.com

as has to be done at the moment. Freeform construction will mean that buildability will no longer be an issue as it has the potential to deliver any geometry – the materials and manufacturing technologies must now catch up with the digital capability.

The implications of automated, 24 hr construction should stabilise supply chain management as demand flow is regulated by the predictable speed of the machinery. As materials technology advances to produce single materials that can vary their properties through applied curing, then the need for fit out and services reduces minimising the number of supply chain companies. This can change our whole perception of building construction for example, by using materials that can conduct electricity through one part and have insulating properties in other parts power and lighting supplies could be embedded within the whole building structure made accessible by mobile outlet points that plug straight into the structure anywhere it is required.

CONCLUSIONS

Although this paper only presents a very brief overview of Rapid Prototyping technology and speculates on its potential to create a new type of construction industry, it can be seen that the change may be radical when it arrives and instead of being used to make models for visualisation, the technology could be used to create full scale buildings. Current applications are being found in small part manufacture particularly those required in low volume that have a high value such as heritage and fine art. Lean production will become an integral part of freeform construction driven by digital fabrication enabling automation, customer responsiveness and certainty of outcome in cost, time and quality.

The challenge for academics will be to forget traditional design and construction methods – anything is possible. No longer will the construction process be confined by the buildability of the design or the need to use sub-contract trades. The focus will eventually be on the creation of high value assets that enhance the lives of all who use them. The challenge for practitioners will be to understand how to change their roles to ensure the potential of this technology is maximised and the opportunities grasped.

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