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Applying future industrialised processes to construction

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ABSTRACT

Construction has traditionally relied on specifications and 2D drawings to convey material properties, performance details and location information. Advanced 3D solid modelling and digital fabrication methods are growing in construction. Iconic building design is driving the industry towards a new era of the Building Information Model (BIM) where a building is modelled entirely using 3D solid CAD tools containing all the required information for construction. CNC machinery can utilise this information to manufacture components enabling highly bespoke and non-repeating components to be cost competitive. Rapid Manufacturing machines also use this information to build components by selectively adding material rather than the traditional subtractive or formative processes. The BIM drives current machines for the production of models for inspection or to explore assembly issues. Recent developments are scaling up these processes so that whole building components can be built using a mega scale, additive machine. This paper explores some of the issues relating to the design of building components and discusses issues on the implementation of these process.

Keywords: Freeform Construction, Rapid Manufacturing, Digital Fabrication, Construction Design

1.1 INTRODUCTION

In the manufacturing sector, automation using industrial robots and machines that used direct numerical control took hold in the 1960s. The development of microprocessors delivered computer numerical control in the 1970s and the IT revolution in the 1980s brought computer aided design software. In the 1990s advanced parametric modelling was introduced and the industry has enjoyed the development of the integration of design and analysis tools and machine control. All these technologies can be found in construction (Howe, 2000; Kolarevic, 2003; Schodek, 2005). The introduction of CAD/CAM for the creation of large structural components for freeform buildings is driving the development of digital manufacturing technologies for construction. However, cutting edge designs for buildings are becoming increasingly unrealisable using the current state-of-the-art methods - new processes are required (Egan, 1998; European Construction Technology Platform 2005). The control of material placement and reducing the number and quantity of materials will play a key role. The manufacturing sector is turning to Rapid Manufacturing (RM) for solutions, especially for the production of highly personalised products (Invisalign, 2006). The construction industry is waking up to the potential that automated additive technologies offer for solving these problems. Ultimately, it is feasible that such new processes will drive down the cost of existing construction, while raising the bar of achievable construction design solutions. New technologies are most likely to find niche applications initially and will eventually filter down to the domestic sector; exemplified by the Tunnelform system (The Concrete Centre, 2004).

Over the last ten years there have been attempts to selectively bond sand and cement to create freeform structures from traditional building materials (Pegna, 1997). RM has developed large mould making processes (The American Foundry Society, 2005) and the first viable large-scale freeform process for construction, Contour Crafting (CC), has been demonstrated in the laboratory at the University of Southern California (Khoshnevis, 2002). Khoshnevis is pushing for the commercialisation of this process in the US. It is capable of producing full scale, freeform wall structures that would replace the structural concrete block wall similar to that found in UK house construction.

Contour Crafting, however, cannot take full advantage the extended functionality that can be embedded within the wall structure if the principles demonstrated by existing RM processes are applied. Precise control of very small volumes of build material would allow the wall to be constructed, ground up, with all the internal pipework, conduits and channels in place, removing structurally redundant material. The implications of such an approach would lead to: clever design solutions using geometric freedom; a smaller number of build materials and a

reduction in the material resource required for construction process; simplify on-site operations with a reduction in complex trade coordination; force the resolution of interface issues, hence reducing part count. Design would be complete up front and would mean that the structure could be designed to be more easily disassembled and recycled at the end of life. In addition, the acoustic, permeability and thermal characteristics can also be modified by 'printing' appropriate, optimised geometry (Buswell, 2006).

A concept domestic wall structure, designed using Freeform Construction principles is depicted in Figure 1.

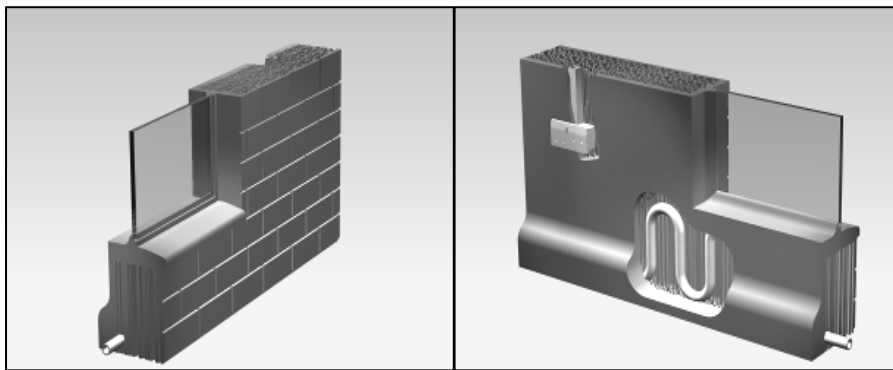


Figure 1: A concept application for Freeform Construction – 'WonderWall'.

New UK research at Loughborough University, is developing a process capable of delivering the concept 'Wonderwall' at full scale. This paper gives details on additive processes and a discussion of the differences between traditional and Freeform Construction is given as background information. The issues surrounding design practice, design tools, and data and information protocols are highlighted.

1.2 ADDITIVE TECHNOLOGIES

There are a family of names used to describe essentially the same type of fabrication technology; Additive Manufacturing, Rapid Manufacturing, Rapid Prototyping and Solid Freeform Fabrication. This method of making physical components is delivered by many types of process; Thermojet, Selective Laser Sintering (SLS), Stereolithography (SLA), 3D printing (3DP), Fuse Deposition Modelling (FDM), are a few (Wohlers, 2004). Typically each of the processes can use a range of materials and all have advantages and disadvantages, suiting them to particular tasks. They all work 'print' 3D structures typically up to 500mm in the x, y and z directions. A design is usually created using 3D CAD solid modelling. A model is first tessellated in much the same way as a Finite Element Analysis mesh is

generated then sliced into layers according to the specific machine parameters. Each slice is sent to a machine. The machine builds the component by sequentially creating and bonding each layer to its predecessor to reproduce the 3D artefact. Applications vary and can be found in the literature and on the web sites of companies offering Rapid Manufacturing services. A good source of further reading can be found at Castle Island (2006). Many classification methods exist for current RM processes. Application descriptions of common RM processes are offered here for discussion of the differences of these in a construction context. Parallels are drawn between these processes, traditional construction methods and both existing and conceptual Freeform Construction technologies.

1.2.1 Comparison of additive process

Figure 2 depicts the process of slicing the CAD model and gives diagrams illustrating the principle features of mentioned processes. Each works on a layer-by-layer basis. The SLA and SLS processes employ a laser; the latter cures a liquid photo-sensitive resin, the former uses the laser to melt a small area of powdered material that then sets to form a solid. The surface finish and fine-ness of detail is dependent on the material properties and the width and intensity of the laser. The laser 'rasters' across the build area with a fine laser. To speed up the build process, both processes outline the solid/liquid or powder boundary on each layer with a fine laser beam profile and then 'fill in' the area with a de-focussed laser or open hatching strategy. As with any process, control of operating parameters is crucial for a successful build. SLS requires a balance of laser intensity, traverse speed penetration and time required to either melt or sinter powder particles into a solid. These parameters are similar with SLA but the phase change mechanism is different. Even when these parameters are tightly controlled, issues arise. For example; the heat generated during the sintering process leaves solidified components embedded in a hot but loose powder 'cake'. If broken open too soon then thermal distortion will affect dimensional tolerances. Table 1 compares the various processes.

The 'drop-on-demand' processes of 3DP and multi-jet deposition epitomise the idea of three dimensional printing. All employ raster based deposition of either phase change build materials or binder systems onto powders and use standard inkjet printer technologies (both PZT and bubble). Fused Deposition Modelling (FDM) refers to a family of processes which extrude a range of thermoplastic polymers to build up a component in much the same way squeezing a tube of toothpaste would.

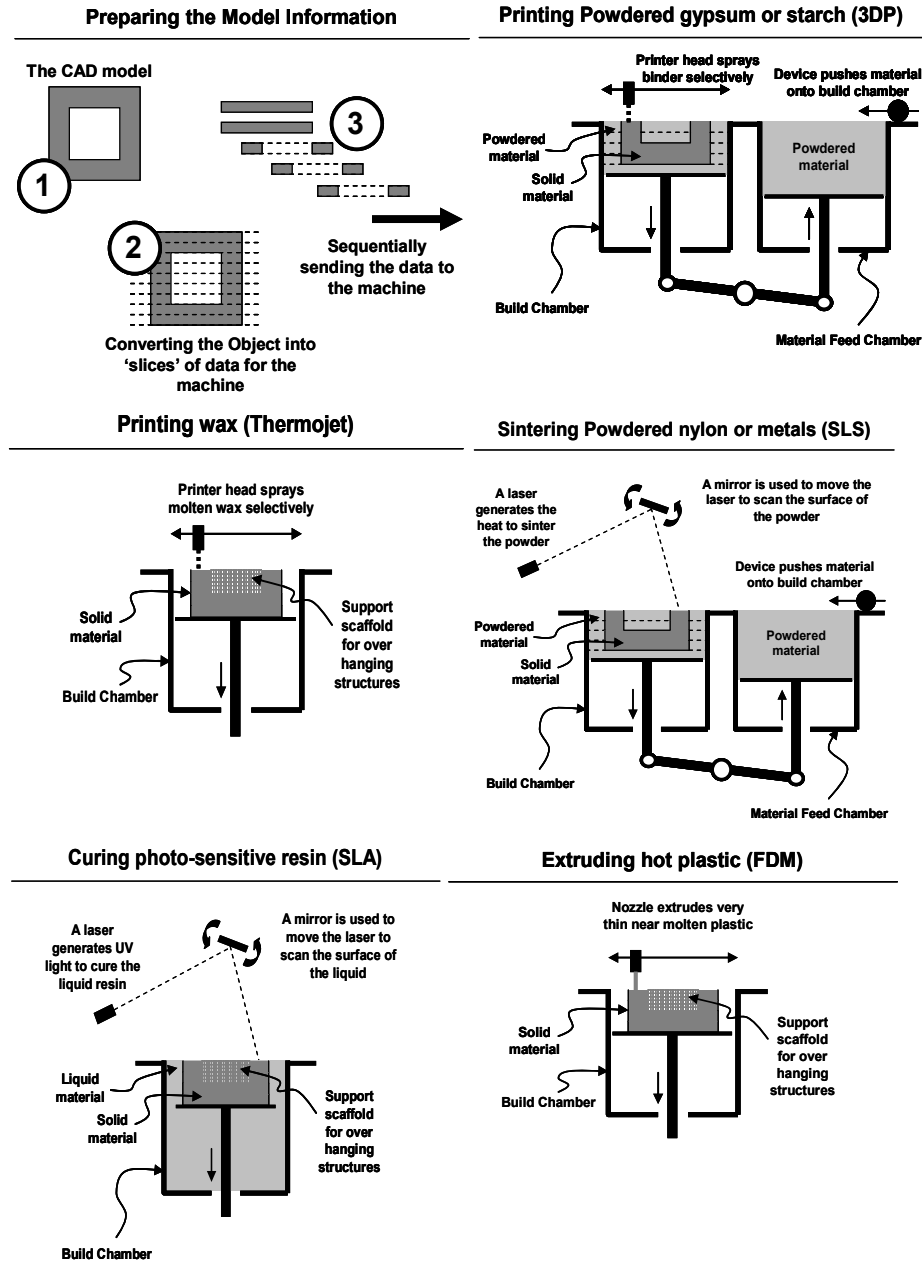


Figure 2: Diagrams depicting several of the most commonly used Rapid prototyping processes.

Table 1 summarises the similarities and differences between the mentioned processes.

		3DP	SLA	SLS	ThermoJet	FDM	CC
Support Strategy	Placement of permanent lintel						■
	Second material					■	
	Scaffold system		■		■	■	
	Powder cake	■		■			
	Self supporting capability		■		■		
Material Delivery	Vat	■	■	■			
	Through deposition device				■	■	■
Phase Change	Thermo set				■	■	
	Curing						■
	Laser melting			■			
	Binding	■					
	Light activated		■				
Post Processing	Removal of scaffold		■		■	■	
	Removal from powder cake	■		■			
	Surface curing (liquid systems)		■				
	Infiltration (part strengthening)	■					
	Surface finishing (scaffold attach)		■		■		
Feature size	Very Fine (< 0.01mm)		■				
	Good (< 0.1mm)			■	■		
	Reasonable (< 1.0mm)	■				■	
	Construction (>19.0mm)						■

Rapid Manufacturing machines are designed to build miniature, hand held and desktop sized items. A site based construction process is unlikely to use a laser augmented approach (SLA/SLS). In addition, the 'vat of material' approach is unattractive, because of the impractical issues associated with post-processing what would be very large components (SLS/3DP). This leaves processes that deposit material through a deposition device (Thermojet/FDM). A key point is that as you increase the build scale, the volume flow of material will force the design of a new process; it cannot simply be scaled up.

For build sizes in the order of 1mm→10mm, the build material can be deposited by a printer head and still maintain a reasonable build speed. Using the printer head to control deposition of a curable liquid allows incredibly fine feature sizes, up to 600dpi (Objet Geometries, 2006).

Between part sizes on the scale of 10mm→100mm it can be cost effective to use a matrix material that has a larger particle size; the ZCorp 3DP process uses powdered gypsum (Z Corp 2006). Instead of passing the build material through the printer head, only a liquid binder is deposited which binds the matrix material. The volume of liquid passed through the head is a fraction of the part volume and hence the build speed is maintained. Larger processes (100→1000mm) cannot get enough binder through a printer head and so only print a curing agent onto a matrix material pre coated with an epoxy based compound (Prometal 2006).

Extruding mineral compounds (CC)

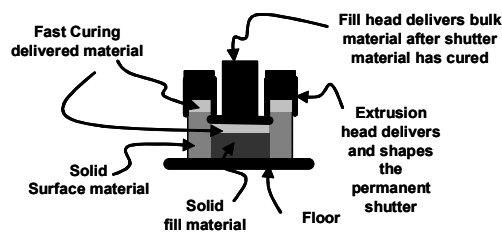


Diagram shows cross section through a liner wall structure

Selectively placing mineral compounds (MRD)

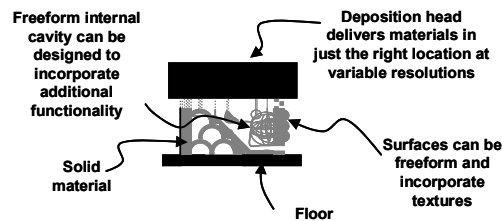


Diagram shows cross section through a wall structure, but the width does not have to be constant

Figure 3: Diagrams of existing and conceptual Freeform Construction processes.

For conceptual larger scale parts, say 1000→10000mm, a special (non-existent) agent would be required so that minute quantities could be used to reduce the print volume flow.

1.2.2 Additive processes for construction

The top diagram in Figure 3 depicts the Contour Crafting process and the process features are in Table 1. Contour Crafting has been tailored for the production of domestic housing wall components. The intention is that a large gantry system will be able to 'print' the entire structure for a house. The process has been demonstrated to produce large structures in the

order of 3m long by 1m high by 0.1m wide. This volume is many times that of the conventional RM processes. In order to deliver these volumes of material an extrusion and back fill approach has been adopted: An inner and outer 'skin' is extruded (~19 by 19mm) and forms a permanent shutter. The machine then backfills with a bulk compound similar to concrete. One of the key issues is how the build material maintains its desired form once it is deposited while it is curing: Contour Crafting uses thixotropic materials with rapid curing and low shrinkage characteristics. The process avoids post-processing by depositing the material using similar principles as the Thermojet technique. So far the process has not been developed to handle overhanging sections, although the strategy for creating openings for doors and windows will be affected by robotic placement of lintels that the deposition head can build off.

The shutter extrusion dimensions limits the feature size that can be created and the process is given to producing long, thin walls that can be curved arbitrarily. The surface finish is towelled as part of the process and can achieve very high degrees of smoothness. The practical wall system that the Contour Crafted structure would be a part of, would also need to be clad, insulated, finished internally, have doors and windows fitted and mechanical and electrical services, etc. added to it. Currently the intent is to leave out sections of the wall as it is 'printed' and post fit services modules that could be either accessible from the outside (flush with the surface), or internal, being built into the wall.

Contour Crafting represents the first generation of Freeform Construction processes. The next generation of technologies will be capable of printing at variable resolutions. A Multi-Resolution Deposition (MRD) device is depicted at the bottom of Figure 3. MRD will build objects at comparable scales and speeds to Contour Crafting, but will be capable of fine detailing that gives RM technologies their strength. The likely specification and process features will be:

- mineral based compounds (cost);
- selective deposition of material (minimising post processing);
- feature size down to ~1mm (control of surface texture);
- variable deposition resolution (high speed fill in);
- material shape holding (allow additional layers while curing);
- high degree of self-supporting features (minimises post processing);
- inclusion of internal voids and channels (adding value through function);
- varying material properties through additives (e.g. for moisture control);
- more freeform surfaces (greater design freedom for free); and,
- more reliable build time and precise tolerances (machine control).

1.3 IMPLICATIONS FOR CONSTRUCTION DESIGN

The MRD Freeform Construction process has been defined. This section discusses implications for construction design and issues associated with design process and information handling. A conventional UK domestic dwelling wall is cited here to highlight differences with the concept wall depicted in Figure 1. This wall might comprise (typically, from the inside out): 3mm coat of finishing plaster to create a hard smooth finish; 12mm render to remove imperfections from the block work in preparation for the finishing plaster; 100mm load bearing concrete block wall bedded using a sand cement mortar; 50mm cavity filled with an insulation eg glass fibre; 100mm clay brick bedded in mortar, tied to the internal leaf with steel ties.

There are 8 materials listed here and typically 2 trades required to erect and finish the wall; the brick layer and plasterer. A complete 'fully functioning' wall could include timber and glass for the doors and windows, employing a combination of glaziers and joiners; a joiner would also finish the wall with timber skirting boards and sills; plastic conduit for electrical wiring, usually embedded beneath the plaster, requiring an electrician and labourer; pipe work and panelled heating devices, usually surface fixed by a plumber. The design now uses nearer 13 materials and 7 trades. In addition, damp-proofing introduces another material and openings in the structure require lintels and usually some sort of temporary former, made in timber, to guide the brickwork. Scaffold is needed to elevate the site operatives to access higher sections of the wall safely. The design becomes a complicated series of interface resolution issues: Damp proofing location and draining round windows; closing cavities; lintel placement; cutting bricks for openings and defining space; weatherproofing round windows and doors.

The MRD process would aim to handle many of these issues with a single operation, utilising reduced numbers of materials. In the example given, this process would replace the original 13 materials with 5; the primary build material, glass, a framing material, probably an insulating material and some additive to the primary material for moisture control. In addition, the thermal performance could be enhanced (Buswell, 2006) and material resource could be minimised by simply not printing structurally redundant sections; and there could be more variation in design because it takes no more effort or expense to print a curved section than it does a straight one. The only costs are; design time, machine setup and run time and material consumption. It is also likely that self supporting structures like arches will be employed to form openings which would reduce the requirement for post processing. Glazing these can be achieved using well established CAM/CAD and CNC technologies. This affects the design of space and form and would mean more client choice and greater use of freeform surfaces.

Designing functionality into the interior of the wall is the real benefit. Designers, architects and engineers would be required to rethink how performance can be achieved and enhanced using solutions based on geometry; using a single material to realise the design goals. The process would need to be integrated and increased use of automated optimisation to derive design solutions would become more likely. In order to achieve this, it is conceivable that CAD software tailored for Freeform Construction design would design rules. These constraints would ensure that the designed structures could be successfully built within the process operating parameters. A process like MRD simplifies the elemental operations to achieve a construction component and limits material options. The key is that functionality is not compromised, just realised in a different way. By simplifying the elemental operations of the construction process, building design criteria and optimisation routines into such software are realisable and therefore greater design variety is afforded with a single process.

1.2.3 Implications for design process

The design process for a part produced using RM and construction are similar. Table 2 highlights this, comparing RM, construction and MRD design process. All three processes describe how to make a physical object and the stages for all are similar. The actual operations and the way in which information is transferred are different. The real difference between traditional construction design process and that used by MRD is how the building information is gathered, stored and utilised. Traditional approaches typically use an 'over-the-wall' approach between design experts. The MRD approach will require simultaneous design because the design of the material placement will affect the integration of structure, function and services while having to satisfy the desired outer form. It is possible that the outside form could be determined by the wall internal structure and the space requirements, rather than working the space design and services integration around a given wall shape.

Table 2: Design process comparison between Rapid Manufacturing, Freeform Construction and traditional construction.

Rapid Manufacturing	MRD Construction	Traditional construction
Specification and brief	Specification and brief	Specification and brief
Concept and ideas	Concept and ideas	Concept and ideas
CAD model	CAD model	Design
STL conversion	STL conversion	Drawing production
STL testing (buildability)	STL testing (buildability)	Analysis of site programme
STL Slicing	STL Slicing	Temporary works
Fabrication	Fabrication	Build
Post processing	Post processing	Remove temporary works
Assembly with system	2nd & 3rd fix	2nd & 3rd fix

1.2.3 Implications for information and ICT

The MRD process will require a digital representation of the component to be built and assumption here is that this will be a 3D solid CAD model. The control of RM machines often uses a the common interface Standard Triangulation Language (STL) file format. STL describes a faceted surface representation of the CAD model. Each triangle has a normal associated with it that indicates which face is 'inside' the component. Simply, the original CAD model is a geometric representation of a shape that defines what is solid and what is not. The format only carries the object information and is not capable of carrying other information, such as *how* to build it. This can be important because the layers created in the vertical direction during a part build in RM can result in non-uniform part material properties, which can be undesirable. The debate over standards continues in the manufacturing sector and the suitability for MRD has yet to be established. Likely issues include:

- size of data required to define large structures;
- quality of representation of surfaces;
- how to handle multiple materials;
- the transition from 2D to solid 3D modelling;
- the effort in design and analysis;
- machine control;
- build information;
- distribution of build 'knowledge' to machine;
- interfacing with existing design tools; and,
- units and tolerances and repeatability.

1.4 CONCLUSIONS

Automating construction will deliver benefits as has been demonstrated in the manufacturing sector. There are two options, one of which is to automate human processes. This approach is flawed for all except very specific tasks because encoding the complexity of handling materials coupled with the highly complex decision making process exhibited by craftsmen is difficult. The second option is to simplify the elemental operations controlled by the computer (Pegna, 1997). Many of these simple operations can be carried out in such a way as to produce a very complex product. This is the essence of Rapid Manufacturing and why the process is so suited to the construction automation issue.

The industry will have to rethink how components are designed to maximise the benefit that a process such as MRD can deliver. The design process will be computer based which is a goal the industry is already moving towards. The MRD device is the focus of ongoing research at Loughborough University.

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