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INVESTIGATION OF THE POTENTIAL FOR APPLYING FREEFORM PROCESSES TO CONSTRUCTION

R. A. Buswell¹, R. Soar¹, M. Pendlebury², A. Gibb², F. Edum-Fotwe² and A. Thorpe²

r.a.buswell@lboro.ac.uk

1 – Wolfson School of Mechanical and Manufacturing Engineering;

2 – Civil and Building Engineering;

Loughborough University, Leicestershire, LE11 3TU.

Abstract

Rapid Manufacturing processes are capable of constructing 3D physical objects directly from digital data by sequentially bonding '2D' layers of material. These processes have been developed to shorten design and production time whilst enhancing competitiveness. The technologies promise to revolutionise many traditional processes in the manufacturing sector and are achieving wide spread acceptance in industries such as aero and automotive engineering.

Within construction, while additive processes abound, the benefits of significant economies and reductions in construction time, as advocated for by Egan, have not been fully realised due to the lack of change in the methods of production. This paper describes Rapid Manufacturing and its processes and demonstrates the case for their application within construction. Consideration is given to the issues in terms of materials, process and cost.

Key Words: Automated Construction, Freeform Construction, Rapid Manufacturing, 3D Printing

INTRODUCTION

Historically, construction has found it difficult to meet the quality expectations of its clients, provide safe working environments for employees and to deliver on time (Latham 1994). Part of this problem is the complex integration of components and processes during construction and a shortage of skilled labour (Egan 1998). In addition, the industry is likely to face increasing pressures from developing environmental issues (Guthrie et al. 1999)

The UK government has been addressing these issues through a succession of initiatives, prompted by the Latham and Egan Reports (Latham 1994, Egan 1998) and ultimately by 'Constructing Excellence.' The drive is towards leaner, better Modern Methods of Construction (Lovell 2003). Some of these issues have been addressed by Standardisation and Pre-Assembly (Gibb, Pendlebury 2003).

The automation of construction processes offers the possibilities of more consistent output, better quality and better environment for operatives in terms of health and safety. To date, construction automation has largely been investigated in terms of robotics (Gambao, Balaguer & Gebhart 2000, Kahane, Rosenfield 2004, Kuntse et al. 1995, Lorenc, Handlon & Bernold 2000, Werner 1995, Williams, Albus & Bostelman

2004, Stein, Gotts & Lahidji). There have been studies based on the potential to automate construction (Scott-Howe 2000). Some large scale automation has been demonstrated by the construction of the Shimizu Corporation building (Yamazaki, Maeda 1998).

Rapid Manufacturing is a collection of additive processes that deliver three-dimensional physical objects directly from digital information and are described in more detail in the following section. These automated processes are achieving wide spread acceptance in many industries and have the potential to impact significantly on traditional construction methods.

RAPID MANUFACTURING

Strictly speaking, Rapid Manufacturing exists only in the application of a number of Rapid Prototyping technologies. Rapid Prototyping has its roots in product design and development. A Rapid Prototyping device is capable of constructing a 3D component from sequential '2D' layers of material. Integral structures and moving parts can be included in components with almost no increase in fabrication complexity.

Rapid Prototyping becomes Rapid Manufacturing if the product can be used directly as an end use component. Rapid Manufacturing can be described as 'the direct production of finished goods from a Rapid Prototyping device.' Such devices deliver finished goods directly from digital data using additive processes, eliminating the requirement for tooling. The evolution of additive processes is freeing the constraints of 'Design-to-Manufacture' and introducing a new era of 'Manufacturing-to-design' (Wohlers 2004).

Increasingly, Rapid Prototyping is expanding into Rapid Tooling; functional models for prototype testing; medicine; as well as delivering enhancements to 3D visualisation and concept modelling. Existing applications for the technology can be found in: Air ducts for Fighter jets; measuring equipment for space; Formula 1 car aerodynamics; gun sight camera mounts for military tanks; hearing aid shells; and submarine replacement parts. Future applications are being found in: the automotive industry; filter technology; archaeology; marine applications; medicine; art; sports equipment technology; textiles and construction (Wohlers 2004).

One of the obstacles for true Rapid Manufacturing is in the quality and precision of the produced parts. For high-end engineering applications, end use parts created from Rapid Prototyping processes cannot yet compete with traditional methods of manufacture. High precision is not an issue for construction and it could be an application where Rapid Prototyping based technologies are able to deliver true end use products.

Rapid Prototyping Technologies

A number of Rapid Prototyping processes are described here(Wohlers 2004). 'Stereolithography' was the first commercially available technique and arrived in 1987. A liquid photopolymer resin is held in a tank. A flat bed is immersed to a depth equivalent to one layer. Lasers are used to activate the resin and cause it to solidify. The bed is lowered and the next layer is built and so on. 'Fused Deposition Modelling'

extrudes a narrow bead of hot plastic and is deposited in just the right location, where it fuses to the existing structure and hardens as it cools. 'Laminated Object Manufacturing' bonds successive layers of material to create a 3D component. A laser can be employed to cut each layer to size. 'Selective Laser Sintering' utilises a laser is used to partially melt successive layers of powder. One layer of powder is deposited over the bed area and the laser just targets the areas that are required to be solid in the final component. 'Direct Metal Deposition' uses powdered material also and can produce fully dense metal parts commonly for dies and mould applications. 'Shape Deposition Manufacturing' bond layers of material that are shaped by a computer numerically controlled cutting/milling tool. 'Contour Crafting' is a fabrication process by which large-scale parts can be fabricated quickly in a layer-by-layer fashion. It has been adapted to create walls. In this application, the process extrudes two clay beads, either side of the wall. This sets quickly and is then in filled with a second, cementitious, compound. The next layer is subsequently laid and the wall height increased. This is achieved using computer controlled robotics. '3D Printing' is a process based on inkjet printer technology. The inkjet heads deposit a liquid binder onto a bed of powder. The binder is applied in the areas that are required to be solid. The binder effectively 'glues' the powder together. There are significant advantages in the application of this process for construction, which are principally, simplicity and scalability.

Rapid Prototyping Processes for Construction

Rapid Prototyping methods have been used for construction applications, but have been largely restricted to concept modelling in architecture (Kvan, Kolarevic 2002, Broek et al. 2002, Burry 2002, Simondetti 2002), or plant development (Melling et al. 1997). Pegna considered a layer deposition method suitable for traditional construction materials (Pegna 1997). Contour Crafting is the first automated layer manufacturing process that has been demonstrated to have the potential for generating civil scale structures directly from digital data (Khoshnevis 2002). Alongside the benefits of automation, processes based on Rapid Prototyping technologies offer additional functionality that is not possible with traditional method of construction. The authors term this technology application, 'Freeform Construction.'

If Freeform Construction process are to be developed, however, there must be realistic drivers. Some of these may be for applications where there is a lack of, or expensive labour; where the environment is excessively hostile; or where light-out or 'zero-noise' construction can be of benefit. These could be based on or off site. Developments in materials and processes will be capable of generating new multi-property, composite and single material, multi property solutions. Beyond this, automated processes could open up new dimensions in architecture, engineering, systems integration and customisation.

MATERIALS

Neglecting waste from excavation, construction currently creates 70 million tonnes of waste per year in the UK alone, four times domestic waste production. Two of the principal ways in which this can be redressed is to create less waste and to recycle (Guthrie et al. 1999). The implementation of Rapid Prototyping processes in construction have the potential to impact on both counts. Waste is reduced because

only the material required in the finished product is consumed, unused material is recycled. Technology holds the key for more recyclable construction materials. Currently, there are 100s of different materials used in construction, exacerbating the problem. Rapid Prototyping techniques offer the possibility of producing single materials with a variety of properties. This can be achieved by controlling the material deposition and binding processes and component geometry during production. By reducing the number of materials used in buildings, recycling becomes a simpler process.

There are many materials used by today's commercial Rapid Prototyping processes. A considerable number of these can be found in construction. Table 1 details the materials associated with some of the available technologies (Wohlers 2004). Table 2 highlights some of the applications of these (and/or similar) materials in construction (Doran 1992, Anon. 2004c). These tables are not a definitive guide, but demonstrate that there is a degree of synergy between materials used in each field.

Materials development is a key issue for Rapid Prototyping and the focus of continuing research. There is significant interest in 'functionally graded materials' where Rapid Prototyping processes are used to deliver different materials that are combined in controlled amounts to create new materials. The material properties can be designed specifically for a purpose. This is not achievable by conventional means.

Today, useful materials for construction are already used by Rapid Prototyping processes. Undoubtedly, new materials will need developing specifically for construction. The combination of these new materials and process design will be pivotal in the success of applying Rapid Prototyping based techniques to construction.

PROCESS

The potential value of Rapid Manufacturing approaches increases with problem complexity. When considering systems that are assembled from many components, this complexity is maximised when the system is manufactured using a single process. Construction poses such a problem, with component integration at the heart of the difficulties it encounters. The issues for Rapid Prototyping based approaches for construction lie in the scale at which it becomes technically feasible and economically viable. The scale of application can be considered at various levels:

- Component, such as a door lock or part thereof;
- building component, such as the prefabrication of the air-conditioning plant;
- building section, such as prefabrication of a complete bathroom;
- whole building, i.e., ground up, foundation to finishes simultaneously.

The various level of application are fully explained elsewhere (Gibb, Pendlebury 2003). At the component level, Rapid Prototyping could impact today. One US company already uses 3D printing in the production of specialist Architectural Mouldings (Anon. 2004a). As the scale increases, so do the number of traditional materials and methods that need to be replaced. The technical issues increase, but the solution for common problems, such as interfaces and junctions, become conceptually more feasible.

Table 1: Rapid Prototyping Process Types and Materials.

Process	Material
Stereolithography	Epoxy, acrylate
Multi-Jet Modelling	Thermoplastic
Selective Laser Sintering	Polyamide, glass-filled and aluminium-filled polyamide, elastomer, polystyrene, stainless steel, ceramic, bronze, sand
Laminated Object Manufacturing	Paper, PVC, plastic
Direct Metal Deposition	Iron alloys, stainless steel, nickel and copper alloys, tungsten-carbide
Fused Deposition Modelling	ABS, polycarbonate, polyphenylsulfone,
Contour Crafting	Clay, cement-based compounds
3D Printing	Plaster, sand, ceramic, starch, Stainless steel (and other metals), sand, thermoplastic, acrylate photopolymer

Table 2: Rapid Prototyping Materials and Their Use in Construction.

Material	Uses in Construction
Aluminium	Windows, fixings, roofing and cladding
Ceramics	Bricks, tiles and drainage systems
Copper	Pipework
Elastomers	Seals in pipework (rubber being the most common)
Sand	Motars, Screeds and render
Epoxy	Adhesives
Steel	Pipework, reinforcement, structural members, fixings, door lock mechanisms
Plaster	Wall finishes and fire protection
Polyamide	Thrust washers and bearings (mechanical plant)
Polycarbonate	Glazing
Polymers	PVA, wood glue; MDPE, gas and water pipework; ABS, pipework, housings, refrigerator interiors and telephones; PTFE, pipes and jointing; Polytetrafluorethylene, bearings, concrete admixtures.
Polystyrene	Insulation
PVC	Window frames, drainage pipework and guttering
Nylon	Control joints, gaskets and gear wheels (mechanisms and mechanical plant)

COST

Cost will play a role in the application of Rapid Prototyping based technologies for construction. Influencing economic viability could be a lack of labour resource, resulting in a relatively high-cost process becoming economically viable. Alternatively, health and safety issues may out-weigh the implementation of

conventional and possibly less expensive construction methods. The bottom line cost of Rapid Prototyping processes suitable for civil scale manufacturing depend on a multiplicity of factors, including; material, process, local economic factors and application scale.

A comparison can be made using construction components that can be manufactured on commercially available Rapid Prototyping machines. In its current form, Rapid Prototyping is particularly suited to the small scale production of small components with complex geometry (Wohlers 2004, Hopkinson, Dickens 2003). A key advantage of Rapid Prototyping is that product customisation comes at no additional cost. This is termed 'added value.' A suitable product in construction is the plaster ceiling rose. These can be mass produced, specialist, or custom made items which have a particular application in heritage building maintenance. There are a range of costs associated with these products. Table 3 details three ~350mm diameter ceiling rose products and their approximate retail value (Anon. 2004b, Morrison 2004, Anon. 2004d). A product requiring a custom made mould would cost a great deal more.

The ZCorporation 810 3D printing system is capable of producing components of this size in plaster and full colour. Table 4 details the cost analysis for reproducing a ceiling rose similar to those listed in Table 3 with this system. The analysis is based on that given in (Hopkinson, Dickens 2003). The part volume has been estimated at 0.003m^3 and it is assumed that the components can be 'stacked' in the build process. The machine capital and maintenance costs are from (Wohlers 2004). The machine utility time and depreciation were taken from (Hopkinson, Dickens 2003) and were 90% and 8 years respectively. The material cost estimates based on data supplied by ZCorporation. Finally, the labour cost estimates were not available. The costs shown in Table 4 are based on the data given for a SLS process, which is also powder based (Hopkinson, Dickens 2003).

From Table 4, assuming an overhead, profit and retail mark-up of 40%, the product cost would be 231.21 Euros. The material cost is clearly significant in determining the part cost. If the plaster and binder costs could be reduced to 3755 Euro/ m^3 and 7510 Euro/ m^3 respectively, the resultant part retail cost would be just 34.38 Euros. These values gives a window in which to consider the economic case, depicted in Figure 1. It can be seen that the 3D-printed product is unlikely to compete with mass production, but it could compete at the specialist end of the market. The added value, not quantified here, strengthens the case:

- Every rose produced could be unique;
- any complexity can be accommodated at no additional cost;
- and there is no waste produced.

Beyond specialist applications, the economic viability for the process to produce civil scale structures will be decided by: The application scale; building complexity; added value in terms of services integration within the structure; and material and process cost.

Table 3: Approximate Retail Prices for Plaster Ceiling Rose Products.

Case	Company	Product	Unit Cost (Euros)
1	C & W Berry Ltd.	Mass produced, UK (Artex-Rawplug). Simple design.	22
2	Heritage Ceilings	Stock Rose, hand painted, AU. Ornate.	103
3	Regency Town House	Stock mould, made to order, UK. Highly Ornate, multi part.	263

*All costs converted to Euros using (Anon. 2004e)

Table 4: Cost Analysis for Plaster Ceiling Rose Production Using 3D Printing.

Part Name	Data	Units
Build data		
Number per platform	19	-
Platform build time (43mm/hour)	14	hours
Production rate per hour	1.4	part/hour
Hours per year in operation (90%)	7884	hours
Production volume total per year	11038	-
Machine Costs		
Machine & Ancillary Equipment	135000	Euro
Equipment Depreciation Cost/year	16875	Euro
Machine maintenance cost per year	14000	Euro
Total machine cost per year	30875	Euro
Machine cost per part	2.80	Euro
Labour Costs		
Machine operator cost per hour	7.07	Euro
Set-up time to control machine	120	min
Post processing time per build	360	min
Labour cost per build	56.56	-
Labour costs per part	2.98	Euro
Materials costs		
Volume of each part	0.003	m ³
Build material cost per unit volume	36657	Euro/m ³
Binder cost per unit volume	49427	Euro/m ³
Cost of material per build	2089	Euro
Cost of binder per build (30% material volume)	939	Euro
Material cost per part	159.37	Euro
Total cost per part	165.15	Euro

CONCLUSIONS

The available technologies in the field of Rapid Prototyping have been introduced. The potential for Freeform Construction has been identified. The issues surrounding materials, process and cost have been discussed. Rapid Prototyping technologies could help deliver better buildings in terms of quality and consistency. They have the potential improve working environments. They may be a solution for technical issues such as material junctions and component integration. New materials and process need to be developed to achieve these goals and the question of process scale

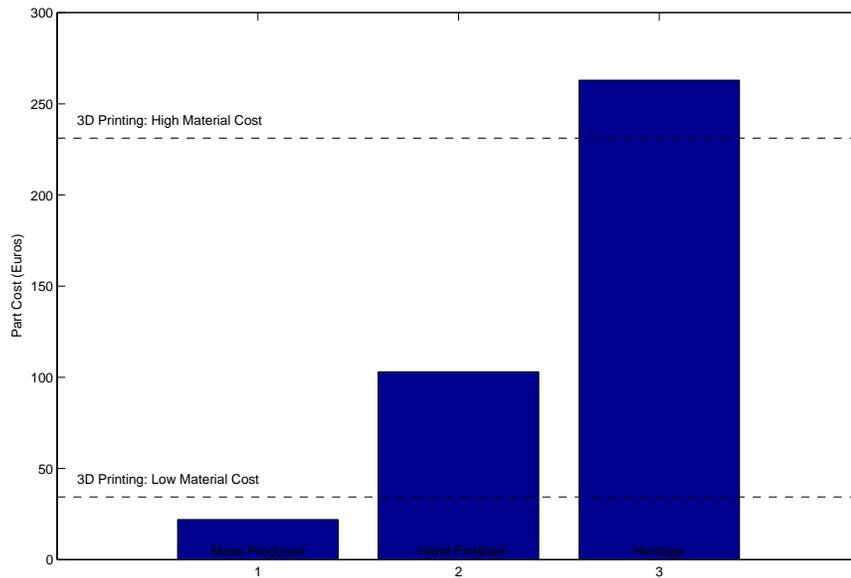


Figure 1: Comparison of Retail Prices for Plaster Ceiling Roses.

has not yet been identified. The implementation of such process will also impact on construction management, labour forces, design processes and contractual obligations. These technologies, however, offer the potential to minimise construction waste, enable new and better engineering solutions and generate new dimensions in architectural freedom.

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