The recent adoption of the term additive manufacturing (AM) to describe a broad range of digital ‘layer by layer’ fabrication techniques comes 20 years since its inception and more than 10 years since architectural practices engaged with the technology for making prototypes and models. Soon this technology will join existing CNC subtractive and formative processes within the volume and mass-market sectors, where design complexity and increased functionality result in competitive advantage. It is also about a decade since researchers proposed additive manufacturing for construction. Rupert Soar and David Andreen introduce here the different construction-scale additive manufacturing systems currently in development. If linked to physiomimetic computational design strategies, these technologies provide novel possibilities for addressing architecture’s manufacturing challenges in the face of energy expenditure, material resources and environmental impact.
Additive manufacturing (AM) has been largely adopted by the automotive, aerospace, military, medical and consumer goods sectors, initially as a method for producing prototype components, then for producing tooling and moulds and, most recently, for ‘end-use’ parts. This evolution reflects improved, selectively curable materials that have extended their performance to match standard engineering polymers and metal alloys. AM has penetrated high-value, short-run and ‘custom’ products due to increased complexity, design flexibility, material utilisation and increased functionality, compared to the traditional engineering processes of forming or machining components. It is no coincidence that layer-by-layer fabrication was adopted from traditional construction, yet we do not view traditional construction as generically ‘additive’. This is because some aspects of construction are additive (building), some are formative (shuttering) and some are subtractive (centring), and, strangely, all three of these aspects can be found in any commercial AM machine. This observation is important, as really AM has nothing to teach construction about layer manufacturing per se, or its ability to form complex internal structures and assemblies within a form.

AM is about to transition to ‘volume’ or mass customisation. This requires new AM processes integrated into manufacturing cells alongside automated handling, assembly, subtractive and formative systems. This capability may have its greatest impact within mainstream volume construction where design integration (for example, monocoque structures), increased performance (dynamic building envelopes), ‘design for disassembly’ and ‘product take-back’ result in clear competitive advantage and global brand identity. This demands the integration of digital design, simulation, manufacturing and assembly as a continuum. Digital construction is ironically a ‘digital vernacular’.

Research around additive manufacturing for construction (AMC) can be traced to 1997, when Joseph Pegna demonstrated a method for the layer-by-layer selective curing and consolidation of cement structures by steam and posited its application for ‘free-form fabrication’ of construction components. However, it is worth noting the passing of a decade since the first attempts to realise AMC. In 2001, Behrokh Khoshnevis at the Viterbi School of Engineering, University of Southern California, described and began assembling the materials and components for a large-scale combined extrusion and trowel ‘automated construction’ system called Contour Crafting. In 2003, exploratory work at Loughborough University focused on large-scale free-form fabrication to assess the feasibility of what was then called ‘rapid manufacturing’ for construction components, from which would emerge a large-scale (4 × 5 × 5 metre/13 × 16 × 16 foot) printing test bed. In 2004, Enrico Dini, then as Freeform Construction (Rupert Soar and Ian Wilkes), MineralStone, 2010 opposite: Additive manufacturing for construction places new demands on selectively curable materials which can satisfy technical, aesthetical and sustainability criteria. MineralStone is an inorganic mineral paste developed to suit a combined additive and subtractive process; it can be selectively triggered to harden into a stone-like machinable construction material.

David Andreen, Duncan Berntsen, Petra Jenning and Rupert Soar, Agent Construction Cluster, SmartGeometry Conference, Copenhagen, 2011 previous spread. Investigation of design processes whereby multiple functions are simultaneously realised within a single structural solution. This emergent structure was realised over four days with volunteers acting as agents with conflicting objectives, such as openness, integrity, permeability, ventilation and connectivity, which must be constantly negotiated towards a solution. The work explores bottom-up negotiated solutions that will produce biological membrane capabilities for building envelopes.
Dini Engineering, based in Italy, patented and trialled a large-format epoxy resin and binder printing machine, and in 2007, inspired by the 3-D printing process, patented an inorganic large-format printing process called D-Shape and formed Monolite UK Ltd to commercialise the first AMc demonstrator. In 2008, Richard Buswell from Loughborough University transformed the large-format printing capability into what is now called ‘concrete printing’. The same year, Freeform Construction Ltd was formed to develop and commercialise the MineralJet process.

Progress has been steady, if not sporadic. The concept of AMc has been driven, encouraged and fostered by many creative minds within architecture who see an output technology to materialise exponentially complex forms. Architecture is rapidly progressing through an era of parametricism to one of morphology, or physiomimetic design. However, the next significant development in AMc is overdue. As AM enters mass-market manufacturing, it will probably first undertake customised operations producing elements that are geometrically close to the final part (‘near net shape’), combined with conventional ‘near net shape’ formative operations and linked to digital or CNC subtractive (‘net shape’) operations as a process continuum. Are the drivers the same for the construction sector? Will the investment opportunities mimic the year-on-year growth seen in the evolution of what was once called a rapid prototyping technology to what is about to become mainstream additive manufacturing?

A Point of Convergence
It is a time for a reassessment of AMc by architectural engineers and the broader construction community. We are some way from on-site AMc, but this does not exclude ‘near site’. However, what is certain is that AMc will first emerge as an off-site capability. Like the adoption of AM into manufacturing, AMc will first address niche markets, but potentially have greater impact within volume markets. For AMc to enter ‘volume’ construction, it must form part of an integrated, digitally driven additive, digital subtractive and digital formative continuum. It must realise greater performance than free-form aesthetics alone. It will enable design freedom combined with greater function, and it must address sustainability head-on. For this to happen, three components must converge. These are new, selectively curable phase-change materials, new processes at construction scales, and new design capabilities from which new product capabilities and applications will emerge.

New Materials
The first commercial, selective phase-change materials for AMc are ‘aggregate/binder’ and paste systems. Two examples are D-Shape’s magnesium oxide aggregate and binder system.
and Freeform Construction's high-density calcium sulphate paste called MineralStone. Unlike concrete, these do not set when mixed with water, but have a chemical ‘trigger’ which selectively activates crystallisation and solidification. Both materials break the cost model used by many AM technology producers; the cost of the machine is offset by the cost of the material supplied, which is typically $100 per kilogram. This model cannot work at construction scales: selectively curable phase-change materials for construction applications must come in at $100 per tonne.

AMC materials must address the future, they must be synthesised from by-product sources, be indigenous to the location where they are transformed into products, and be fully recyclable within both the factory environment and at the end of the product’s life. This latter requirement could be an entry point for AMC products and components ‘designed for disassembly’. Selective activation must induce crystallisation, but not instantaneously. At the scale of partitions, panelisation and cladding systems, crystallisation should take place over minutes, not seconds, to reduce exothermic heat, which can be cumulative at these scales.

Where D-Shape’s and Freeform Construction’s materials may differ is in their application. D-Shape’s material is a concrete substitute immediately suited to external, load-bearing and monocoque applications, and Freeform Construction’s material is for non-load-bearing internal applications where high-tolerance and high-density (polished) finishes are required. However, there could be greater benefit in integrating these materials in a single monocoque solution, ie structure and finish. Both companies have developed their materials for near net shape additive fabrication, but Freeform Construction is deliberately linking an additive near net shape capability to a subtractive net shape detailing operation in one process.

**New Processes**
Contour Crafting tackled one of the first issues of fabrication at construction scales: how to deposit bulk quantities of material (with a centimetre-scale nozzle) to keep the build times down, while resolving micron-scale detail required for the finish. It simultaneously extrudes at the macroscale, then shapes at the microscale. It can work at more than two scales of resolution within any single deposited layer; by ‘extrude trowelling’ rapid curing walls or a ‘skin build’, the space inside the part can be backfilled with a generic concrete. This points to a departure from conventional construction methods that begin assembly at the metre scale and proceed downwards, with each subsequent operation, down to the micron scale with the polished finishes on surfaces. This cannot be carried out in a single operation, so components representing each scale of the structure are assembled a piece at a time. To overcome the...
inevitable discrepancies and ‘tolerance drift’ when assembling an estimated 3,000 components in a typical house, construction is as much about designing interfaces, seals and gaskets as it is about the physical production of the form.

AM currently fills the niche for objects from approximately 1 cubic millimetre (0.00006 cubic inches) up to 1 cubic metre (35 cubic feet). Layer fabrication techniques, however, extend well into the micrometre (printed circuits) and increasingly the nanometre scale (silicon chips). Likewise, above the scale of ‘things you can see or hold’, there will not be one single or ‘mega’ scale, but many ‘niche scales’. Contour Crafting could exploit ‘on site’ at scales covering rooms to buildings. D-Shape could exploit ‘near site’ at scales covering pods to rooms. Concrete Printing could exploit ‘on site’ for foundations and primary structures, and Freeform Construction’s proposed MineralJet exploits ‘niche scales’ above 1 cubic metre (35 cubic feet) up to pods, partitioning, cladding and panellisation.

The concept of testable prototypes of a structure is relatively new, and is satisfied largely by simulation and visualisation software. However, architects, when communicating with their clients, need detailed model-making capabilities above 1 cubic metre (35 cubic feet), for 1:50 up to 1:500, and urban planners need detailed models at 1:1000. These models typically require builds greater than 1 cubic metre (35 cubic feet), but detail at less than 1 cubic millimetre (0.00006 cubic feet), which could be achieved by combining additive and subtractive methods into a single process. Architectural engineers are discussing the value of structural and detailing prototypes for models at 1:5 to 1:1 scales — (within build volumes of 3 to 5 cubic metres (106 to 176 cubic feet) — for interface design or wind tunnel testing, and these too require smooth micron-scale finishes that only a subtractive process can deliver.

Freeform Construction’s solution is an interchangeable deposition head that is swapped with a cutting-tool head during the build. They are not pursuing a predefined articulated robot or gantry-type placement device. Gantry robots are easy to assemble and cheap to run, but the build envelope is commonly restrained within a frame. Inversely, articulated robots are expensive to run, but are not tied to movements within a building envelope. An articulated robot with an additive deposition and/or subtractive fabrication head can work inside pods, build artefacts of a greater size than itself, and move fabricated parts and components around a factory as part of a sequence of operations. This becomes relevant for cladding and panellisation systems, for example.

To fabricate a set of custom high-performance panels, as part of a secondary cladding retrofit, digital scan data of the building is captured on site and a digitally generated functional skin created to enhance U-value, acoustic and service utility criteria.
while satisfying window and door detailing and so on. The digital skin is then sectioned (at 2 × 3 metres/6.5 × 9.8 feet for handling) into approximately 50 custom cladding panels. The panels may be between 100 and 400 millimetres (3.9 and 15.7 inches) thick, depending on the performance criteria, and must be fabricated at 3 to 5 millimetre (0.1 to 0.2 inch) resolution within a day, as part of a 24-hour unmanned operation. Panels have a void-to-solid ratio of around 80:20, which is nearly one panel every 30 minutes and approximately 20 litres (4.4 gallons) of build paste. They must be printed, textured/finished (meaning external face texturing and building interface detail to match the existing building profile), cured, and have the interface profiles machined on to each panel edge, before batching and transport at less than £250 per panel.

New Design Tools
Digital design to manufacturing begins with digitising of the input parameters. This may include the physical scan of an existing building, the continuous scanning of the construction process on site, and could extend to measures of physical properties, such as moisture permeability, thermal flux or usage and behavioural data. This data must be processed through algorithmic design tools and traditional design processes to deliver solutions that fulfil specified performance criteria, whether stylistic, programmatic, environmental or functional. In this context, AMc is not actually an end stage, but part of a continuum of inputs and outputs feeding to and from each other, resulting in the complete documentation of a structure’s performance (through algorithms) ‘as built’, which implies that, like AMc (digital outputs), 3-D scanning (digital inputs) needs to be fully integrated into the manufacturing process. This overturns linear ‘design and build’ processes and replaces them with a continuous loop existing in both physical and virtual space from which modifications and adaptations to existing designs can be generated through the building’s life.

By removing the bottleneck between digital design and fabrication, both detail and non-standardisation emerge which may well be classed as a ‘digital vernacular’. Emerging design methodologies challenge standardisation. NURBS modelling, optimisation, scripting and simulation often lose their logic when taken through realisation stages. AMc provides the means to undo this conflict as it removes the manufacturing constraints on customisation and complexity. This is not a complete departure from standardisation, but, rather, a shift from physical, component-based standardisation to a virtual standardisation that places completely new demands on both the execution and regulation of the industry. In this new environment we are forced to remodel the relationship between the plan and the object. These are no longer separate. Designing at the process level of a building and its occupants –

Freeform Construction
(David Andreen and Petra Jenning)
MineralSkin
2010

Digitally generated prototype wall section demonstrating integrated function within an auto-generated script environment. The process could be generated directly from scan data and performance data (for example, thermal and moisture flux) of an existing building requiring secondary cladding.
Physiomimetic computational design (PCD) operates on this algorithmic process level. PCD links the form-finding relationships in a script directly to a materialisation process, where agents interrogate a process database (for example, movement of gas, waste, light, access, even aesthetics) to identify a set of optimal materials from which a single structure that meets all these process requirements can be fabricated. The output data from the materialisation process links directly to the inputs or variables in the script, which contains the spatial relationships for each material and the processes it represents. PCD overcomes the problem of trying to miniaturise separate process components within less space by folding the process components and sharing the material capabilities across multiple functions. It produces structures that literally squeeze more functions into less form and can be output directly to AM or AMc. PCD is not inspired by, nor mimics, either the forms or functions in nature. It mimics matter folding and process component integration as a natural outcome of agents negotiating for materialisation, which is nature.

Moving Forward
Though AM technologies emerged within mechanical engineering, their adoption took them far wider into aerospace, military, medical and leisure markets, to name just a few. AM has moved from a prototyping capability, with year-on-year growth for 20 years, to a niche high-value ‘end-user’ customisation tool, and is about to integrate within mainstream volume manufacturing. Interest in AM by the construction sector has been sporadic, partly because of the disconnect between design and construction, but mostly as there is an issue of scale. A model-making capability is fine for an architectural practice, but cannot be applied to the 1:1 of building components. However, the expectation of AM’s imminent engagement with volume markets is triggering progressive construction companies to look again at the technology and ask what gains can be had.

Commercial AMc processes will initially address high-value markets, with products of capitalisable complexity, but will readily penetrate volume off-site markets by ‘breaking the model’, where off-site construction companies feel they must match the look of traditionally built on-site buildings. Build it free-form and customer expectations rise, and the competition with traditional on-site construction evaporates. Some global construction companies are already aware that, like cars and consumer goods, design and engineering are integral to innovative manufacturing.

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The first $AM_c$ products to enter the market may well be less spectacular than some of the visions, but no less significant.
Between the two institutional (University of Southern California and Loughborough University) and two fledgling commercial groups (Freeform Construction and Monolite) in Europe and the US that have engaged with this task, much ground has been covered over the last decade. Each has taken a unique approach based largely on issues of scale, resolution and cost. Each has developed new and novel, selectively curable phase-change materials, which either reflect current material resources or look forward to address the pressures of sustainability, recycling, ‘design for disassembly’ and ‘product take-back’. Each has produced novel process solutions, each selecting niche scales, niche deposition solutions and niche resolutions, which, when considered as a whole, greatly mitigate the entry-point decisions many in the construction industry will be making over the next few years. The first AM_C products to enter the market may well be less spectacular than some of the visions, but no less significant.

Rupert Soar, Integrated Utility Node, FP7 I3Con project, Loughborough University, 2008 and Smart Geometry Conference, Barcelona, 2010

Integrated service utility node concept showing how scripts can be driven by function. HVAC and ME processes are integrated within a single system. The solution explores space saving by: 1) the proximity of the ‘process space’ for each service; 2) the sharing of materials across multiple services and functions; and 3) outputting an exoshell structure to the stereo-lithography apparatus (SLA). Low-melt alloys and flexible polymers were injected within the interstitial spaces separating each process. The injected metal alloys and polymer form contiguous shells within the structure to satisfy multiple functions simultaneously: metal for strength, shielding and conduction, and polymers for sealing, insulation and ductility within a single structure.