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Three-dimensional printing in the construction industry: A review

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Three-dimensional (3D) printing has long been used in the manufacturing sector as a way to automate, accelerate production and reduce waste materials. By using this technology, it is possible to build a wide variety of objects if the necessary specifications are provided to the printer and no problems are presented by the limited range of materials available. With 3D printing becoming cheaper, more reliable and, as a result, more prevalent in the world at large, it may soon make inroads into the construction industry. Little is known, however, of 3D printing in current use in the construction industry and its potential for the future, and this paper seeks to investigate this situation by providing a review of the relevant literature. In doing this, the three main 3D printing methods of contour crafting, concrete printing and D-shape 3D printing are described, which, as opposed to the traditional construction method of cutting materials down to size, deliver only what is needed for completion, vastly reducing waste. The paper also identifies 3D printing's potential to enable buildings to be constructed many times faster and with significantly reduced labour costs. In addition, it is clear that construction 3D printing can allow the further inclusion of building information modelling into the construction process, thus streamlining and improving the scheduling requirements of a project. However, the current 3D printing processes are known to be costly, unsuited to large-scale products and conventional design approaches and have a very limited range of materials that can be used. Moreover, the only successful examples of construction in action to date have occurred in controlled laboratory environments and, as real world trials have yet to be completed, it is yet to be seen whether it can be equally proficient in practical situations.

Keywords: 3D Printing; contour crafting; concrete printing; D-shape; building automation

Introduction

The construction industry has traditionally relied on specifications and two-dimensional (2D) drawings to convey material properties, performance details and locational information − using small-scale models, typically constructed of wood − to create the object for evaluation as part of the design process. Increasingly, specifications and 2D drawings are being replaced by three-dimensional (3D) modelling in the virtual environment of building information modelling (BIM). Another alternative to 3D modelling is the use of advanced 3D solid modelling techniques in combination with digital fabrication methods (Buswell 2008). This form of modelling is known as *rapid prototyping* and saves time by negating the human modeller or toolmaker (Buswell 2007). Rapid prototyping is an automated process referring to techniques that produce shaped parts (models) usually using 3D printing or 'additive manufacturing' technology, wherein successive layers of material are laid down under computer control (Hague & Reeves 2000). These processes contrast with traditional methods that are either subtractive, starting with a block and machining away material that is not required, or formative, shaping or casting material in a mould (Buswell 2007). In broad terms, components are made by adding, or building up, material to form an object. In this process, the 3D objects are 'sliced' and represented as a series of 2D layers, with layer-based processes sequentially adding each layer to build up the desired object. It is the selectivity and control of the material that enables the freedom to manufacture (or 'build') any desired geometry, which is the fundamental advantage of these processes over more conventional techniques (Buswell 2008).

In recent times, construction 3D printing has begun to move from an architect's modelling tool to delivering full-scale architectural components and individual elements of buildings, e.g., walls and facades (Lim 2012). According to Bassoli et al., (2007), 'The techniques based on layer-by-layer manufacturing are extending their fields of application, from the building of aesthetic and functional prototypes to the production of tools and moulds for technological prototypes or pre-series'. Specifically, large-scale 3D printing, such as 'mega-techniques', is becoming more and more relevant especially since 29 March 2014 when work began on the world's first 3D printing house (Wainwright 2014).

Little, however, is known of the full role that 3D printing currently plays in the construction industry and where this technique could be headed in the future. This paper, therefore, provides a literature review and describes the advantages and limitations of three selected mega-sized 3D printing techniques, i.e. contour crafting, concrete printing and D-shape − their current use in construction and potential for future application in the construction industry.

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Construction 3D printing

According to Lim (2012), there are a number of drivers pushing construction towards automation, with the main ones being reduction in labour for safety reasons, reduction in construction time on site, reduction in production costs and an effort to increase architectural freedom. Vähä (2013) adds quality, reliability, life cycle cost savings and the simplification of the workforce as further considerations. Automated bricklaying, sprayed concrete and precast techniques are some of the numerous examples of automation that are already in use the construction industry (Lim 2012), and construction 3D printing is essentially is just another tool available on the market. The main forms of printing are contour crafting, concrete printing and D-shape as described below.

Contour crafting

Contour crafting is a layered fabrication technology that appears to have great potential in the automated construction of whole, small structures including some of their subcomponents. Dr. Khoshnevis, who has developed contour crafting technology, claims that with this process a single house or even a whole estate of houses may be constructed in a single run with the possibility of each having a different design (Khoshnevis 2004).

Contour crafting, as a workable building system, has been in development for some years. It works on the principle of emitting multiple layers of a cement-based paste against a trowel, which allows a smooth surface finish to be obtained (Lim 2012). Figure 1 shows the application of contour crafting in building construction. As can be seen in the figure, a gantry system carrying a nozzle moves on two parallel rails that have been installed on the construction site (Khoshnevis 2004). The computer-controlled gantry runs the same as a small-scale 3D printer, with thick liquid concrete being squeezed out of the nozzle one layer at a time. The lower layers, having been given time to partially cure, are hardened enough to support the weight of the freshly layered cement (Smith 2012). The contour crafting method differs from other 3D printing methods, with the key feature being the use of two trowels to create a surface on the object being fabricated that is exceptionally smooth and accurate (Khoshnevis 2004). Because of the layer-by-layer fabrication method, contour crafting−based systems have the potential to build utility conduits within walls. This makes the automated construction of plumbing, electrical and structural steel networks within the structure possible (Khoshnevis 2003). It is claimed that by using contour crafting technology it is possible to build a square foot of wall in less than 20 seconds, a whole room in an hour and a 200 m^2 single-storey house in a day (Smith 2012).

The automation involved with this method is so complete that the only fixtures that need to be installed by human workers are doors and windows, which the device is unable to customize (Khoshnevis 2003). Because of the superior forming capability of the trowels used in contour crafting to create smooth and accurate surfaces, geometric shapes with almost no limitations of complexity can be created (Smith 2012). It is thus claimed that because of its speed and the ability

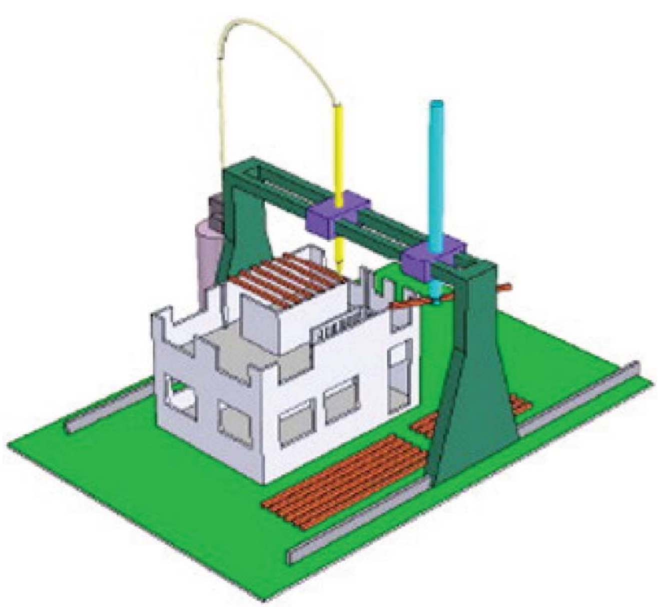

Figure 1. Construction of a building using contour crafting on a gantry (Bosscher et al. 2007).

to use *in situ* materials contour crafting has potential use in two areas: (1) low-income housing or emergency sheltered housing and (2) architectural buildings involving complex shapes that would be expensive to build using traditional methods (Khoshnevis 2003).

Concrete printing

As with contour crafting, concrete printing also involves extrusion of cement mortar in a layer-by-layer process. This print process can be carried out without the use of labour-intensive formwork and has the ability to incorporate functional voids into the structure (Lim et al. 2011). However, the process has been developed without the trowels used in contour crafting so that a smaller resolution of depositing is required to achieve greater levels of 3D freedom. This smaller level of print resolution has, however, resulted in a greater control of internal and external geometries (Lim 2012).

Again, compared to contour crafting, the finishing and post-processing of concrete printing differ because it produces the characteristic ribbed finish (see Figure 2), which can be controlled and designed to exploit the effect. However, if a smooth finish is required, either the wet material is trowelled during the building process or the printed finish is ground to a smooth surface. This must all be completed manually because this step is not yet automated (Lim 2012).

It should be noted that the layered structure is likely to be anisotropic, as voids can form between the individual filaments of the cement paste (see Figure 3), weakening the structural capability (Le & Austin 2012). As Le and Austin (2012) note, the bond between filaments, as well as between layers, influences the hardened properties of concrete components. Therefore, a high strength in compression and flexure as well as tensile bond is the main attribute of this approach. Additionally, a low shrinkage is essential as the freeform components are built without formwork, which could accelerate water evaporation in the concrete and result in cracking (Le & Austin 2012). Because of these issues associated with substandard building materials, an in-house high-performance 'cementitious' material has been developed with a high strength (around 100−110 MPa in compression) − approximately three times that of conventional concrete − to compensate for the weaker structure of layered components (Lim et al. 2011).

D-shape

The D-shape process uses layers of powder and adhesive rather than the cement-like paste used in other methods. This involves a powder deposit process, where the 'powder' is selectively hardened using a binder, in much the same way as in the usual 3D printing process. Each layer of the material is laid to the desired thickness, compacted and then the nozzles mounted on a gantry frame deposit the binder where the part is to be solid. Once a part is complete, it is dug out of the loose powder bed (Lim 2012) (Figure 4). This automated building system, which uses sand and binder to create stone-like freeform structures, enables the constructions of full-size sandstone buildings without human intervention (Tibaut & Rebolj 2014).

The D-shape process has many advantages over traditional formative processes (the use of formwork with concrete) as well as other construction 3D printing processes. This process can use any sand-like material and produces little waste, as the leftover sand, which has not stuck to the object, can be reused elsewhere. The materials used are all naturally occurring

Figure 2. A concrete printed object. Note the ribbing on the side from the layered approach (Austin et al. 2012).

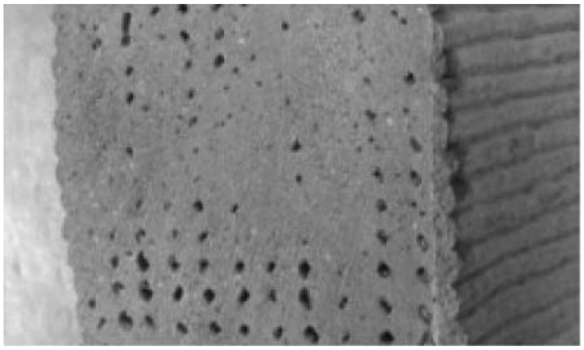

Figure 3. Sectional view of a concrete printed wall. Note the voids formed between the filaments (Le & Austin 2012).

substances requiring very little processing before use in the fabrication process and so the end product is very similar to natural stone (Tibaut & Rebolj 2014).

Comparison of the three techniques

The 3D printing techniques of contour crafting, concrete printing and D-shape are all similar in that all three build additively. However, each of the three processes has been developed for different applications and materials, with each having distinct individual advantages (Lim 2012). One of the main differences between these processes is whether the head mounting (the part that actually delivers the material to the object) is frame, robot or crane mounted. Contour crafting has been developed to be a crane-mounted device for on-site, *in situ* applications. Both D-shape and concrete printing are gantry-based off-site manufacturing processes, although with an appropriate amount of modification there is no reason why both processes cannot be used *in situ* (Lim 2012).

Another major difference between these techniques is the way in which each handles situations where an overhang would exist on the structure. As construction 3D printing relies on building an object from the bottom upwards, overhangs create a particular challenge to these techniques when a section of building requires support. There are two main methods by which overhangs are handled in 3D printing. In the first method, an another material is printed in the void to create a very fine section of scaffold that can be broken away later once support is no longer required. The second method, which is used only in the D-shape system because of its powder-based practice, involves the placement of unconsolidated material, which provides support and is later removed once the drying process is over (Lim 2012).

The last important difference in the three techniques is the 'print resolution', which is actually the amount of material laid down in each pass of the device. Concrete printing and D-shape place 4–6 mm of material for every pass, as compared with the 13 mm that contour crafting inserts – the principle trade off involved being layer depth versus the build speed (Lim 2012). A smaller amount of material laid results in a longer time taken to reach the desired height, but a smaller

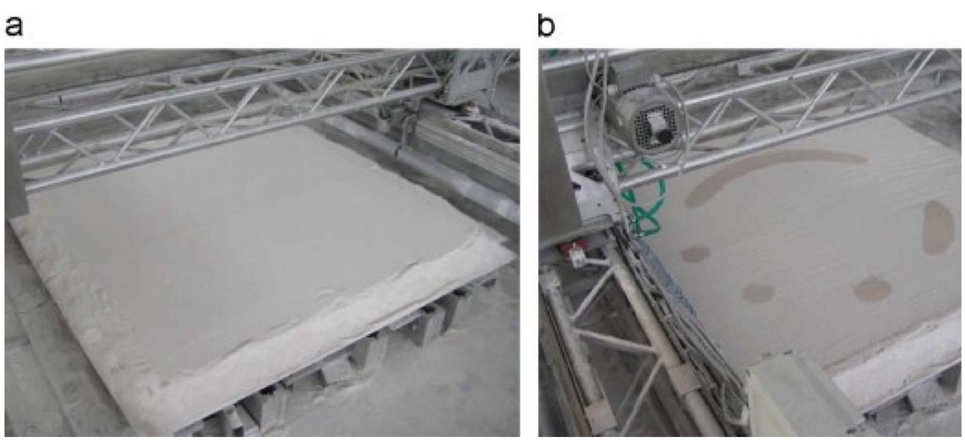

Figure 4. (a) A layer of deposited material ready for adhesive. (b) A cross section of the model that has just been printed (Cesaretti et al. 2014).

amount of material being laid also means a finer control over detail and finish. Figure 5 shows an example of an object that can be printed by each of these techniques.

What construction 3D printing techniques can do for the industry

Design uniformity is an essential part of creating affordable and constructible buildings (Buswell 2008). However, clients in recent years have begun requesting more unique and less uniform buildings and concept designs, which are often abandoned because of the extra costs involved. This constraint on original thinking can be overcome by large-scale 3Dp methods that are able to deliver non-repeating components at a cost-effective price provided relatively low volumes of production are required. According to Pegna (1997), because 3D printing technology offers on-site construction automation, it would be able to reduce the dependence on labour and hence reduce the risk of injuries and weather stoppages. As a result, it is estimated that the technology would be able to reduce construction costs by up to 30% (Pegna 1997)

These techniques are also able to drastically reduce the lead time to production as well as the cost of design and manufacture of more complex parts that would be difficult or impossible to make with more traditional construction methods (Han & Jafari 2003).

Waste reduction

The construction industry has long been a leader in waste production. In terms of resource consumption, it is estimated that 40% of all raw materials used globally are used in the construction industry (Lenssen 1995), with an estimated three to seven tonnes of waste generated during the construction of a typical single-family home (Khoshnevis 2003). This is further compounded by the harmful emissions that construction activities generate.

Construction machines built for 3D printing may be fully electric and therefore emission free, but one of the main energy conservation features is the need for less people, which results in less vehicles being driven to and from the construction site and, in turn, saving large amounts of fuel (Smith 2012). In addition, the accurate nature of additive

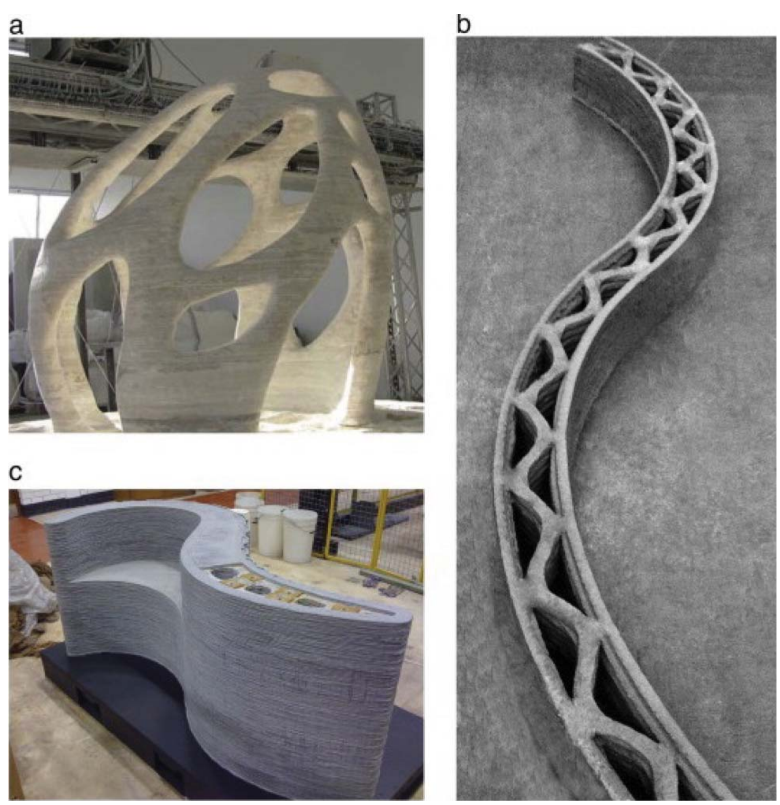

Figure 5. An example of the product that each printing process can achieve. (a) D-shape; (b) contour crafting; (c) concrete printing (Lim 2012).

fabrication enables 3D printing techniques that result in little to no material waste (Khoshnevis 2003). This reduction in waste is brought about in a number of ways, chief among which is the lack of requirement of formwork and mould making. In buildings, almost every wall, panel and partition is uniquely dimensioned, which means that for construction to be cost-effective either standard size materials are cut to fit or custom moulds are made to form each part. Construction 3D printing allows the printer to obviate these approaches and just produce what will actually be needed for the final structure – freeing designers to create what they want and where they want without the need for economies of scale to keep the cost down (Lim 2012).

Furthermore, large-scale printing allows the integration of mechanical and electrical services within the structure, resulting in reduced amounts of wasteful and time-consuming builder's work (Buswell 2007). This, in essence, allows the building to be considered as a homogenous unit, negating the need for difficult interface detailing, reducing the chance of error and hence costly remedial work (Buswell 2007).

Further incorporation of computer modelling

As Lim (2012) notes, the development of BIM will undoubtedly increase the use of digital information and will likely drive the application of automated modelling and manufacturing processes in construction. This is further supported by Vähä (2013), who comments that the automation of building production requires the exploitation of information models in each phase of the working process, i.e., the use of BIM throughout the construction lifecycle. In addition, Vähä (2013) outlines four types of data acquisition needs required by an automated construction process: (1) positioning, (2) tracking, (3) progress monitoring and (4) quality control.

BIM is often used to visualize sensor readings in construction and facilities management for the location and tracking of resources (Vähä 2013). This heavy incorporation of computer modelling that construction automation brings is both necessary and advantageous to the industry. Buswell (2007) observes that the coupling of digitally controlled processes with solid modelling techniques will mean greater design freedom at no extra cost. These savings can be found in places such as complex cores and cavities in an object, which can be produced directly from a CAD model, complete with all necessary systems and avoid the construction of patterns and core boxes that would otherwise be necessary (Bassoli et al. 2007).

This enforced digitalization that automation brings can help in rectifying of the problems that already exist in the industry and specifically where 3D printing is concerned. According to Bak (2003), 'the great advantages, in terms of relatively low costs and very low times for casting availability, contrast with the very poor knowledge concerning the limits of application and the process performances'.

Implications for labour

There is a growing skills shortage in the construction industry and this shortage will be further compounded in the future as a result of aging population in the United Kingdom, Australia and many other countries (Buswell 2007). With safety still a major issue in the construction industry – construction sites being one of the most hazardous environments encountered – it is clear that action is needed. Use of mega-sized 3D printing reduces the number of personnel required on site at any one time because machines such as those used in contour crafting are lightweight and can be quickly assembled, disassembled and transported by a small crew. In addition, the construction operation can be fully automated so that only minimum supervision is required (Zhang 2013).

When used on small residential buildings, the full-scale machine splits into three pieces in order to fit onto a small flatbed truck, minimizing the labour required in transportation and logistics. In contour crafting also, with the vast majority of the construction on site being automated, humans play a supporting role. They lay out supplies for the robotic arm and prepare fresh batches of concrete, as well as complete tasks such as installing windows and doors that are not worth automating or not yet automated (Smith 2012).

Speed

Khoshnevis (2003) claims that the contour crafting method increases the building construction speed to a great extent. He states that estimates show that the contour crafting method will be capable of completing the construction of an entire house in a matter of hours (e.g., less than 2 days for a 200 m^2 two-storey building) instead of several months. This increase in speed of the building process directly results in an increase in efficiency of logistics and management (Khoshnevis 2003).

The increase in speed can be attributed to construction 3D printing methods always operating at a steady and unrelenting pace, unlike more traditional methods that include breaks for workers or concrete curing. Figure 6 shows an example of this increase in speed as first proposed by Buswell (2007), who describes the production of a typical wall section found in a domestic home. The wall is assumed to be 5 m long and 3 m high and is to be made up of a 13 mm of internal plaster finish on 100 mm concrete blocks, with a 50 mm cavity and 100 mm external facing bricks. Fixings, brick ties, insulation, etc., are not included in the example. The figure compares the more traditional building method (dotted line) and the 3D printing process (solid line).

The steps in the traditional methods come from having to leave every 1 m height (approximately) in brickwork overnight for the mortar to set (the maximum weight allowed on wet mortar). Accepting that there is no operational efficiency in the labour allocation (continuous work) and neglecting the set-up time for the machine, 3D printing is comparable in building time to traditional methods because it can work at a constant rate with every layer it places being supported by the layers underneath.

Limitations of construction 3D printing

Since the early years of the 20th century, automation has grown and prospered in almost all production domains other than the construction industry. The adoption of automation into the industry has been slow due to multiple factors, with the most common ones being (Khoshnevis 2004; Hwang & Khoshnevis 2004; Vinodh et al. 2009):

- unsuitability of the available automated fabrication technologies for large-scale products
- conventional design approaches that are not suitable for automation
- a significantly smaller ratio of the quantity of final products as compared with other industries
- limitations in the materials that could be employed by an automated system
- economic unattractiveness of expensive automated equipment
- managerial issues

Moreover, buildings are unlike many other products in that they cannot be easily mass-produced (Hodson 2013). Each building is a prototype of its own, built on different sites, with different conditions, and different materials for different clients. All of this results in a product that is hard to standardize or make amenable to computerization (Hodson 2013). Despite the differences, all three designers of the 3D printing processes believe passionately that 3D printing will eventually make a radical contribution to construction. However, they acknowledge, too, that the technology is so ‘disruptive’ that the cautious and conservative nature of the industry will inevitably make its diffusion a slow process, at least initially (Smith 2012).

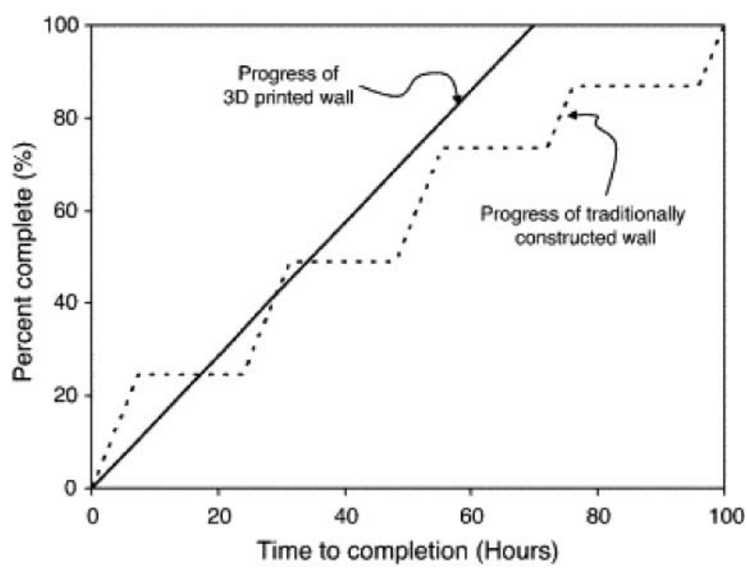

Figure 6. A time graph showing the time taken to complete a wall constructed both by the traditional method and using 3D printing process (Buswell, 2007).

Appropriateness for large-scale/mass development

Construction components of significant size are heavy, typically being up to 5 tonnes. This makes lifting and moving parts an endeavour to be avoided where possible. This means that the *in situ* deposit approach − printing parts on site followed by assembly or ultimately printing large parts of a building or other infrastructure *in situ* − would be a good option for the production of a structure. The disadvantage of construction 3D printing *in situ*, however, is the sensitivity of the materials and processes to ambient conditions that could interfere with on-site applications (Lim 2012). In addition, materials in all three techniques harden through a curing process (contour crafting and concrete printing processes both being wet processes while D-shape is mainly a dry process). This results in a curing process that is inherently less controllable than the heat or UV-based methods of conventional building methods (Lim 2012). Other physical constraints that need to be considered during the entire construction process whilst printing include (Zhang 2013):

1. The nozzle idle time cannot be too long, otherwise concrete may solidify and block the machine.
2. The lower layer must be able to support the upper layer, therefore the time interval between depositing subsequent layers cannot be shorter than the minimum curing time.
3. Subsequent layers must be able to adhere, therefore the interval between depositing subsequent layers should not exceed a critical limit.
4. The printing nozzles cannot be allowed to collide with the previously deposited layer or other nozzles when travelling, because if this happens then when moving between the end points of wall segments, the nozzle may not be able to travel in a straight line in order to avoid obstacles.

These factors, together with the limitations of strength of the materials that can be used in 3D printing, suggest that conventional building methods are likely to continue to be used for multi-storey, heavyweight buildings involving straightforward building processes and that 3D printing would be best for lightweight structures that are 'funky but expensive'. Only later, once the technology has grown and the features have become cheaper, is its use envisaged for more mainstream projects (Khoshnevis in Smith 2012).

Current cost of the technology

Although automation has advanced in manufacturing, one of the main problems facing large-scale construction 3D printing is that its growth in the construction industry has been slow. This is because the conventional methods used in automated manufacturing do not lend themselves to the construction of large structures with internal features (Khoshnevis 2004). This inflexibility can be attributed to several factors, but the fundamental problem is that design approaches in construction are not suitable for automation. Any object that is to be produced by an automated system must first be wholly designed and outlined on a program able to fit with the system capabilities as well as an additional assembly sequence having been written for the object (Khoshnevis & Hwang 2006). All of this comes at an additional cost and relies on advanced planning.

Additionally, construction 3D printing has a smaller production quantity compared with other methods. It can only be used as a solution when identical or similar products are mass-produced (Khoshnevis & Hwang 2006). There is a severe limit in material choices when using 3D printing processes (Khoshnevis 2004) because there only certain materials that can pass through these machines and still be able to be used in the intended way without either destroying the machine or deforming the object that is being constructed.

Perhaps of most significance is that these techniques are accompanied by high initial equipment costs as well as significant ongoing maintenance costs (Khoshnevis & Hwang 2006). This type of automation requires significant start-up fees and specially (and expensively) trained operators. In addition, every new site involving a printer would have different individual needs that must be programmed into the machine to be taken into account thus resulting in additional costs and time. Moreover, the automated systems that would operate in the outside world on dirty worksites would need frequent downtime for cleaning and maintenance.

Finally, an additional obstacle to the implementation of the technology is the need for support systems. As Smith (2012) comments, for example 'What's the point in having a technology which can build a house in a day when the US building inspectors come out 10−12 times to check things over and it take weeks to schedule all the appointments?'.

Conclusions

With clients asking designers for structures that cannot be built by any known method today, new processes such as 3D printing techniques are a likely solution. Also, with factors such as the need to reduce production costs and time on site, additional safety concerns, a push to increase architectural freedom, raising standards of quality and a wish to simplify the work to counter the lack of skilled workers, the construction industry is gradually edging closer to automation. This is particularly the case with construction 3D printing techniques and their advantages such as the ability to produce nonstandard buildings/nonrepeating sections at a reasonable cost, which was virtually impossible earlier. Just the ability to go straight from a computer program to the manufacture of a structure reduces the lead time by such a degree that major cost savings are made in this alone. Adding savings of up to 30% in waste reduction makes construction 3D printing a very attractive proposition indeed.

On the other hand, the technology has some severe limitations for use in construction work. The current unsuitability for automated processes for truly large-scale fabrication, the severely limited scope of the materials that are currently able to be used in construction, the high price that would have to be paid by the pioneers of the industry in simple things such as training, organization and management, together with the price of the equipment itself, are quite prohibitive. Furthermore, the support of local building associations must first be established if such relatively simple matters as building inspections are to be completed in a sufficiently timely and competent manner.

For construction 3D printing methods to be successful in the future, there must be features for all the processes involved to be able to be performed onsite with little to no effect of the everyday outdoor conditions of building sites. An additional issue is that with equipment involving robotic workers, the technology should be easy to use and have intuitive user interfaces and be able to share work spaces with workers as well as encompass a high level of safety (Vähä 2013). Without such functionality, it seems likely to present-day observers that automated construction 3D printing will not be in widespread use for many years to come.

References

Austin S, Lim S, Le T. 2012. Mix design and fresh properties for high-performance printing concrete. Mater Struct. 45(8):1221.

Bak D. 2003. Rapid prototyping or rapid production? 3D printing processes move industry towards the latter. Rapid Prototyping J. 23(4):340−345.

Bassoli E, Gatto A, Iuliano L, Violante, MG. 2007. 3D printing technique applied to rapid casting. Rapid Prototyping J. 13(3):148−155.

Bosscher P, Williams R, Bryson S. 2007. Cable-suspended robotic contour crafting system. Automat Constr. 17(1):45−55.

Buswell R. 2007. Freeform construction: mega-scale rapid manufacturing for construction. Automat Constr. 16(2):224−231.

Buswell R. 2008. Design, data and process issues for mega-scale rapid manufacturing machines used for construction. Automat Constr. 17(8):923−929.

Cesaretti G, Dini E, Kestelier X. 2014. Building components for an outpost on the lunar soil by means of a novel 3D printing technology. Acta Astronaut. 93:430−450.

Hague RJM, Reeves PE. 2000. Rapid prototyping, tooling and manufacturing, Vol. 117. London: iSmithers Rapra Publishing.

Han W, Jafari MA. 2003. Process speeding up via deposition planning in fused deposition-based layered manufacturing processes. Rapid Prototyping J. 9(4):212−218.

Hodson H. 2013. Robo-builders deliver architects' dreams. New Scient. 22−23.

Hwang D, Khoshnevis B. 2004. Concrete wall fabrication by contour crafting. Los Angeles: University of Southern California.

Khoshnevis B. 2003. Toward total automation of on-site construction an integrated approach based on contour crafting. Los Angeles: University of Southern California.

Khoshnevis B. 2004. Automated construction by contour crafting—related robotics and information technologies. Automat Constr. 13 (1):5−19.

Khoshnevis B, Hwang D. 2006. Contour crafting − a mega scale fabrication technology. Manufact Syst Eng Ser. 6:221−251.

Krutha J-P. 1998. Progress in additive manufacturing and rapid prototyping. CIRP Ann Manufact Tech. 47(2):525−540.

Le T, Austin S. 2012. Hardened properties of high-performance printing concrete. Cement Concrete Res. 42(3):558−566.

Lenssen JR. 1995. A building revolution − how ecology and health concerns are transforming construction. Washington, DC: World-watch Institute.

Lim S. 2012. Developments in construction-scale additive manufacturing processes. Automat Constr. 21:262−268.

Lim S, Buswell R, Le T. 2011. Development of a viable concrete printing process. Proceedings of the 28th International Symposium on Automation and Robotics in Construction, (ISARC2011), Seoul, South Korea, 29th June−2nd July 2011, pp. 665−670. Internatl Assoc Automat Robot Constr.

Pegna J. 1997. Exploratory investigation of solid freeform construction. Automat Constr. 5(5):427−437.

Smith D. 2012. Printed buildings: an international race for the ultimate in automation. Constr Res Innov. 3(2):26−31.

Tibaut A, Rebolj D. 2014. Interoperability requirements for automated manufacturing systems in construction. J Intelligent Manufact. DOI: 10.1007/s10845-013-0862-7.

Vähä P. 2013. Extending automation of building construction—survey on potential sensor technologies and robotic applications. Automat Constr. 36:168−178.

Vinodh S, Sundararaj G, Devadasan SR, Kuttalingam D, Rajanayagam D. 2009. Agility through rapid prototyping technology in a manufacturing environment using a 3D printer. J Manufact Tech Manage. 20(7):1023−1041.

Wainwright O. 2014, March 29. Work begins on the world's first 3D-printed house. Available from: The Guardian: http://www.theguardian.com/artanddesign/architecture-design-blog/2014/mar/28/work-begins-on-the-worlds-first-3d-printed-house

Zhang J. 2013. Optimal machine operation planning for construction by contour crafting. Automat Constr. 29:50−67.