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3D printing in the Construction Industry: a review

Abstract
3D printing (3Dp) has long been used in the manufacturing sector as a way to automate, accelerate production and reduce waste materials. It is able 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 3Dp 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 3Dp in current use the construction industry and its potential for the future and this paper seeks to rectify this situation by providing a review of the relevant literature. In doing this, the three main 3Dp methods of contour crafting, concrete printing and D-shape 3Dp 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. Also identified is 3Dp's potential to enable buildings to be constructed many times faster and with significantly reduced labour costs. In addition, it is clear that construction 3Dp can allow the further inclusion of Building Information Modelling into the construction process - streamlining and improving the scheduling requirements of a project. However, current 3Dp 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 it equally proficient in practical situations.

Key Words: 3D Printing; Contour Crafting; Concrete Printing; D-shape; Building Automation.

Introduction
The construction industry has traditionally relied on specifications and 2D drawings to convey material properties, performance details and locational information – using small-scale models, typically constructed on wood, to create the object for evaluation as part of the design process. Increasingly, these are being replaced by 3D modelling in the virtual environment of Building Information Modelling (BIM). An alternative is the use of advanced 3D solid modelling techniques in combination with digital fabrication methods (Buswell, 2008). This form of modeling is known as *rapid prototyping*, saving time by the negation of the human modeller, or toolmaker (Buswell, 2007). Rapid prototyping is an automated process referring to techniques that produce shaped parts (models) and is usually done using 3D printing (3Dp) or "additive manufacturing" technology in which successive layers of material are laid down under computer control (Hague and 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. To do this, the 3D objects are be '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 3Dp has begun to move from an architect's modelling tool to delivering full-scale architectural components and individual elements of buildings such as walls and facades (Lim, 2012). This is further supported by Bassoli, Gatto, Iuliano, & Violante, (2007) who state that "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 3Dp such as 'mega techniques' is becoming more and more relevant especially since 29 March 2014, when work began on the world's first 3Dp house (Wainwright, 2014).

Little is known, however, of the full role that 3Dp currently plays in the construction industry and where it could be headed in the future. This paper, therefore, provides a literature review in which the advantages and limitations of three selected mega sized 3Dp techniques - contour crafting, concrete printing and d-shape – are described, their current use in construction and potential for future application in the construction industry.

Construction 3Dp

According to Lim (2012), there are a number of drivers pushing construction towards automation: a reduction in labour for safety reasons, reducing construction time on site, production costs and an effort to increase architectural freedom. This is supported by Vähä (2013) who adds quality, reliability, life cycle cost savings and the simplification of the workforce as further considerations. There are already numerous examples of automation on construction sites in the form of automated bricklaying, sprayed concrete and precast techniques (Lim, 2012). Construction 3Dp is essentially is just another tool available on the market.

Contour crafting

Contour crafting is a layered fabrication technology that appears to have great potential in the automated construction of whole, small structures that includes some of their subcomponents. It is claimed by the inventor that, by using this process, a single house or even a whole estate of houses may be constructed in a single run while still being possible for each to have a different design (Khoshnevis, 2004).

Contour crafting, as a workable building system has been in development for some years. It is based on the practice of emitting multiple layers of a cement-based paste against a trowel, which allows a smooth surface finish to be obtained (Lim, 2012). The application of contour crafting in building construction can be seen in Figure 2, where a gantry system carrying a nozzle moves on two parallel rails that have been installed on the construction site (Khoshnevis, 2004). From here, 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). From here the contour crafting method differs from other 3Dp methods, 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 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). Because of this, it is claimed that contour crafting is able to build a square foot of wall in less than 20 seconds, a whole room in an hour and a 200m^2 single storey house in a day (Smith, 2012).

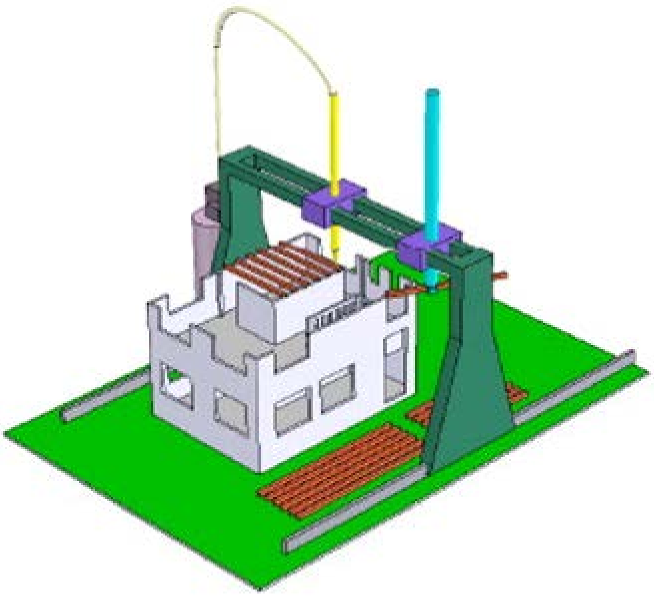

Figure 1 - Construction of a building using contour crafting on a gantry (Source: Bosscher, Williams & Bryson, 2007)

The automation involved with this method is so complete that the only fixtures that need to be installed by human workers are the door and window pieces that the device is unable to customise (Khoshnevis, 2003). Because of the superior forming capability of the trowels used in contour crafting to create smooth and accurate surfaces, the method it is able to create geometric shapes with almost no limitations of complexity (Smith, 2012).

As a result, it is claimed that, due to its speed and ability to use *in-situ* materials contour crafting has potential 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 is also based on the extrusion of cement mortar in a layer-by-layer process. This print process can be carried out without the use of labour intensive formworks and has the ability to incorporate functional voids into the structure (Lim, Buswell, & Le, 2011). However, the process has been developed without the trowels used in contour crafting so that a smaller resolution of depositing is needed to achieve greater levels of 3D freedom. This smaller level of print resolution has, however, resulted in the greater control of internal and external geometries (Lim, 2012).

Again, compared with contour crafting, the finishing and post processing of concrete printing differ. This is because, due to its nature, concrete printing produces the characteristic ribbed finish seen in Figure 3, which can be controlled and designed to exploit the effect. However, if the desired finish is to be smooth, it requires either trowelling wet material during the building process or subsequently grinding back the printed finish to a smooth surface. This must all be completed by hand because it is not yet feasible to be automated (Lim, 2012).

Figure 2 - A concrete printed object: Note the ribbing on the side from the layered approach (Source: Austin, Lim & Le, 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 as seen in Figure 4, weakening the structural capability (Le & Austin, 2012). Further, Le & Austin (2012) note that 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 dangers 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 - in order to compensate for the weaker structure of layered components (Lim, Buswell, & Le, 2011).

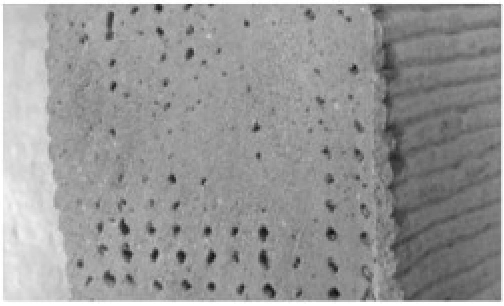

Figure 3 - Sectional view of a concrete printed wall: Note the voids formed between the filaments (Source: Le & Austin, 2012)

D-shape

The d-shape process uses layers of powder and adhesive rather than the cement-like paste used by the other methods. This involves a powder deposit process, where the ‘powder’ is selectively hardened using a binder, in much the same way as the usual 3Dp process. Each layer of 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 then dug out of the loose powder bed (Lim, 2012) (Figure 5). This automated building system, which uses sand and binder to create stone-like freeform structures, enables full size sandstone buildings to be made without human intervention (Tibaut & Rebolj, 2014).

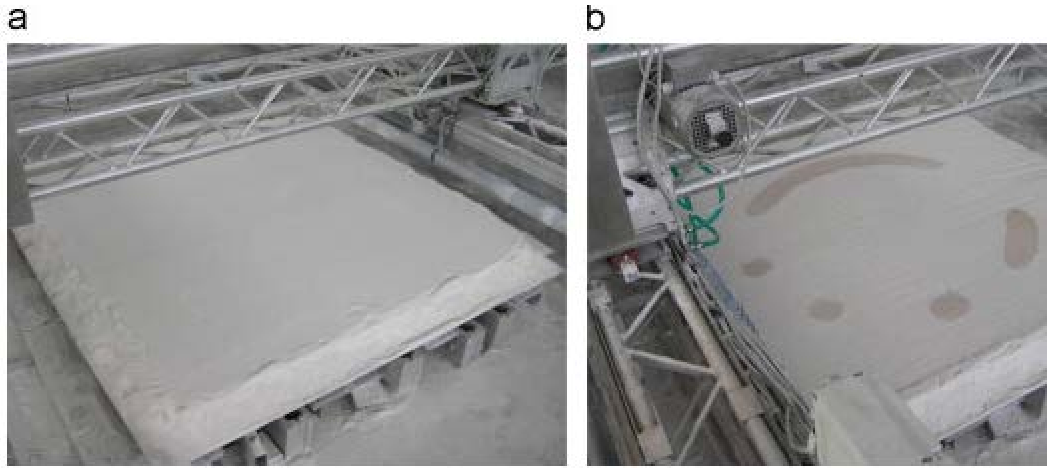

Figure 4 - a. A layer of deposited material ready for adhesive; b. a cross section of the model that has just been printed (Source: Cesaretti, Dini, Kestelier, 2014)

The system has many advantages over traditional formative processes (the use of formwork with concrete) as well as other construction 3Dp processes. It is able to use any sand-like material and produces little waste, as the remaining sand that has not adhered to the object can be reused elsewhere. The materials used are all naturally occurring substances that require very little processing before use in the fabrication process. This results in an end product that is very similar to natural stone (Tibaut & Rebolj, 2014).

Comparison of the three techniques

The 3Dp techniques of contour crafting, concrete printing and d-shape are all similar in that they all build additively. However, each of the processes has been developed for different applications and materials, which has resulted in each having distinct individual advantages (Lim, 2012). One of the main differences 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 they handle situations where an overhang would exist on the structure. As construction 3Dp 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 ways that 3Dp methods handle overhangs. The first is where another material is printed in the void in order to create a very fine section of scaffold that can be broken away later once support is no longer required. The second way is only used by the d-shape system, as it is a powder-based practice. This involves the placement of unconsolidated material, which provides support and is later removed once the drying process has been completed (Lim, 2012).

The final important difference in the techniques is the ‘print resolution’. This concerns the amount material laid down in each pass of the device. With concrete printing and d-shape placing 4–6mm of material for every pass, as compared with the 13mm 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, bearing in mind that a smaller amount of material being laid also means a finer control over detail and finish. This can be seen in Figure 1, which provides an example of an object that can be printed by each of these techniques.

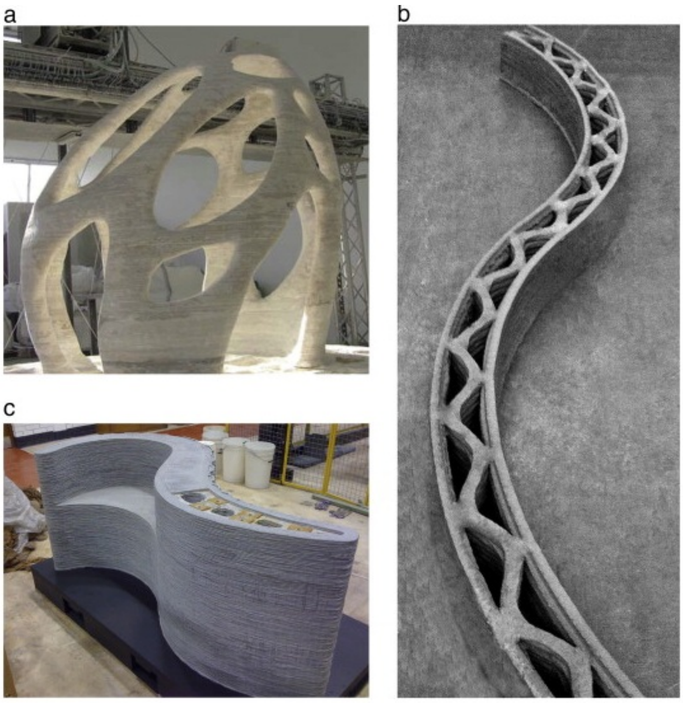

Figure 5 - An example of the product that each printing process can achieve (a. d-shape; a. contour crafting; c. concrete printing.) (Source: Lim, 2012)

What construction 3Dp 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. Of this aspect, Pegna (1997) notes that, because the 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 on the construction industry (Lenssen, 1995), with an estimated three and seven tonnes of waste generated by the production of a typical single family home (Khoshnevis, 2003). This is further compounded by the harmful emissions that construction activities generate.

Construction machines built for 3Dp may be fully electric and therefore emission free, but one of the main savings is from the need for less people resulting in less vehicles being driven to and from the construction site, saving large amounts of fuel (Smith, 2012). In addition, the accurate nature of additive fabrication enables 3Dp 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 saving 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 3Dp 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 Building Information Modelling (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 the 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 visualise 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, Gatto, Iuliano, & Violante, 2007).

This enforced digitalisation that automation brings can help in rectifying of the problems that already exist in the industry and specifically where 3Dp is concerned. As stated by Bak (2003), when discussing 3Dp, “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 on labour

There is a growing skills shortage in the construction industry, which will be further compounded in the future by the aging population in the UK, Australia and many other countries (Buswell, 2007). With the additional problem of safety still a major issue -the construction industry being one of the most hazardous environments encountered - it is clear that action is needed. Mega-sized 3Dp is able to reduce the amount of personnel required on site at any one time. This is 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, minimising the labour required in transportation and logistics. Again using contour crafting as an example, 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 too hard to automate (Smith, 2012).

Speed

The creator of the contour crafting method claims great increases in building speed for those utilising his method. 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 few hours (e.g., less than two 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 3Dp methods always operating at a steady and unrelenting pace, unlike more traditional methods that include breaks for workers or concrete curing. An example of this increase in speed can be seen in Figure 6, 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 3Dp process (solid line).

The steps in the traditional methods come from having to leave every ∼ 1 m height in brickwork overnight for the mortar to cure (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, 3Dp 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.

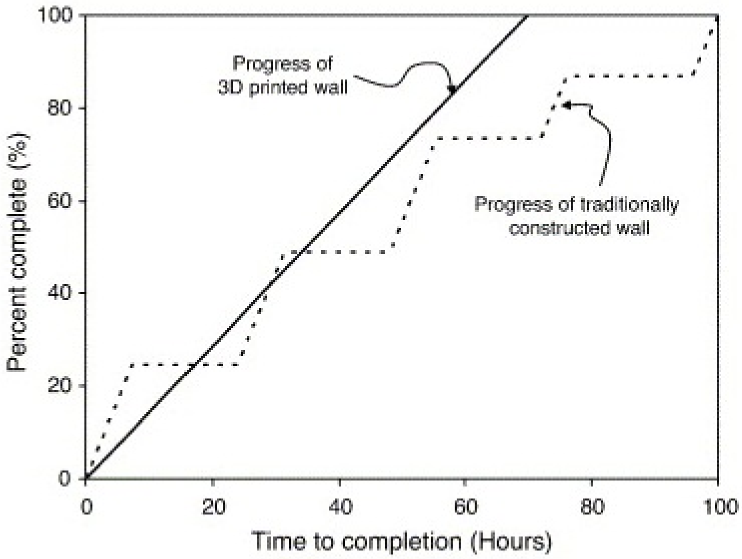

Figure 6 - A time graph showing the time taken to complete both a traditional and 3Dp wall (Source: Buswell, 2007)

Limitations of construction 3Dp

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, chief among which are (Khoshnevis, 2004; Hwang & Khoshnevis, 2004; Vinodh, Sundararaj, Devadasan, Kuttalingam, & Rajanayagam, 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 and
- 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 standardise or make amenable to computerization (Hodson, 2013). Despite their differences, all three designers of the 3Dp processes believe passionately that 3Dp will eventually make a radical contribution to construction. However, they acknowledge, too, that the technology is so 'disruptive' that the cautious and conservative nature industry will inevitably make its diffusion a slow process, at least initially (Smith, 2012).

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 production of a structure. The disadvantage of construction 3Dp *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, with the 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 (Lim, 2012). Moreover, several physical constraints need to be considered during the entire construction process whilst printing, comprising (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 traveling. Because of this, 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 3Dp, suggest that conventional building methods are likely to continue to be used for multistorey, heavyweight buildings involving straightforward building processes, and that 3Dp 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

One of the main problems facing large-scale construction 3Dp is that, although automation has advanced in manufacturing, 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 3Dp has a smaller production quantity compared with other methods. It can only to be used as a solution when identical or similar products are mass-produced (Khoshnevis & Hwang, 2006). In addition, there is a severe limit in material choices when using 3Dp processes (Khoshnevis, 2004). This is because there only only certain materials that can pass through these machines and still be able to be used in a way they are intended 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 for them to be taken into account – 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 “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?”.

Conclusion

With clients asking designers for structures that cannot be built by any known method today, new processes such as 3Dp techniques are a likely solution. In addition to this, 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 3Dp techniques and their advantages such as the ability to produce nonstandard buildings/nonrepeating sections at a reasonable cost, that was virtually impossible previously. 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, makes construction 3Dp 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, organisation and management, together with the price of the equipment itself is 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 manor.

For construction 3Dp methods to be successful in the future there must be an ability for all the processes involved to be able to be performed on site 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 3Dp will not be in widespread use for many years to come.

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