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Innovative building technologies 4.0: Fast-tracking housing delivery through 3D printing

A house fulfils a fundamental need for human habitation. Acquisition of a house (through purchase or construction) is probably one of the greatest expenses for most people in South Africa. However, the complex South African housing industry has two markets: one market financed by the private sector and the other subsidised by the government. Despite several measures put in place by the government, the housing backlog in South Africa is still unacceptably high, at more than 2.3 million houses.[1]

Furthermore, in South Africa, there have been challenges of limited uptake of innovative building technologies in house construction. Fairclough[2] and Burger[3] have noted that innovations have changed how homes are made in many countries, their performance, affordability, and functionality. Although the South African regulatory environment is not prescriptive in the materials and products used in building construction, there has been a slow uptake of innovative building products compared to that in other countries. In this article, the term 'innovative building products' refers to any non-conventional building products that have been assessed and certified by Agrèment South Africa[4] (www.agrement.co.za). There are no South African National Standards to assess the performance of these products. The use of innovative building products in South Africa has important economic ramifications, including eradicating the housing backlog, providing better-quality housing and construction products, and possibly reducing the life cycle cost of the houses.

South Africa can deliver more than 160 000 houses and 80 000 houses per year in the government subsidised and private sectors, respectively, as evidenced in the 2008/2009 financial years shown in Figure 1. Since 2009, the delivery of government subsidised houses has been dropping at an alarming rate, indicating serious intervention required by government and private developers in the home-built environment. This, therefore, requires a change: an exploration of how innovation, in its broad context, can be utilised to examine the structure, characteristics, and technologies available to accelerate the delivery of houses.

A general reluctance by the construction industry to embrace technological advancement has meant that productivity is low, outdated, and lacking in dynamism and creativity. There are various contributory factors. For example, there is an insufficient collaboration between technology suppliers and contractors, inadequate knowledge transfer from one project to the next, fear and anxiety by built environment professionals to explore innovative ideas and solutions, and misperceptions on cost and acceptability of the technologies. However, the construction industry is well positioned to refine its business-as-usual productivity and efficiency models and embrace technological advances such as building information modelling, 3D printing, and augmented reality.[5,6] This article explores the potential of using 3D printing technologies to fast-track the delivery of quality houses in South Africa.

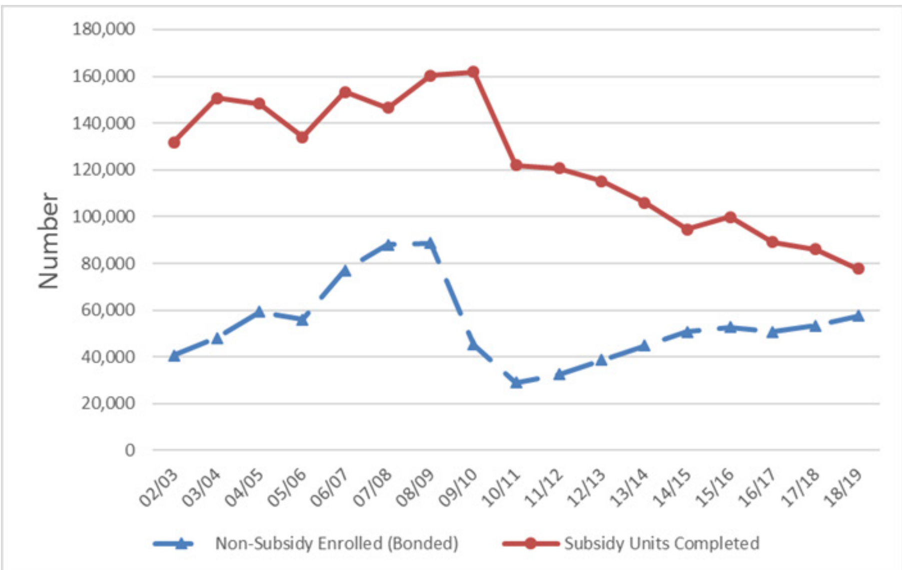


Figure 1: Delivery of houses (adapted from Mahachi[1]).

Significance of the research

Three-dimensional (3D) construction printing is an innovative technology that will significantly alter the way housing will be delivered in South Africa. However, the following questions and issues need to be addressed to support the effective delivery of sustainable human settlements:

- Is 3D printing technology an appropriate future technology in a developing country such as South Africa? Is it a transformative technology that could revolutionise the house construction industry and level the playing field?
- Do 3D printing technologies offer more cost-effective products than conventional 'brick and mortar' construction?
- Conventional construction offers houses a minimum design life of 50 years. What is the life span of a 3D printed house?
- Do 3D printed houses lower operating costs (life cycle costs) over the life span of the houses compared to conventional construction? Are housing beneficiaries and developers interested in reducing operating costs in the long term, or are they only somewhat interested in short-term cost savings? Considering the current and possible future energy crisis, do housing beneficiaries appreciate the present value of energy savings over the design life of the houses?
- How easy is it to maintain and re-model a 3D printed house, and will the products be locally available during the design life of the house?
- The National Home Builders Registration Council (NHBRC)[7] is a state entity established in terms of the *Housing Consumers Protection Measures Act (Act 95 of 1998, as amended)* with a mandate to protect housing consumers through the provision of a 5-year structural warranty. If a structural defect occurs within the warranty period, the home builder must rectify the defect. However, if the builder is unavailable or fails to rectify, the NHBRC[7] is expected to make good the structural defect. Therefore, do the NHBRC[7] and its remedial contractors have the capacity and capability to remedy a 3D printed house to its original state without further compromising its structural integrity?
- With government moving towards quick economic recovery, is 3D printing the right technological solution to assist with quick delivery of houses (permanent and temporary)? Is investing in 3D construction printing technology sustainable, and is there a willingness by construction companies to invest in long-term innovation?
- Small- and medium-sized contractors are now dominating the low-income house construction – is there adequate capacity and resources to invest in 3D construction printing?

Innovation in housing

Before exploring the potential of 3D construction printing, it is necessary to review the building regulatory environment. Performance-based building standards are concerned with what a building product is required to do, rather than with how it is done. Extensive work in this area has been reported by Fairclough[2], Foliente[8] and Hartkopf et al.[9]. The International Council for Research and Innovation in *Building* and Construction (CIB)[10] has also adopted this approach in their definition of a performance-based building. The South African building regulatory framework is also based on a similar performance-based approach. The framework provides for all buildings to comply with the National Building Regulations[11] and *Building Standards Act (Act No. 103 of 1977)*, using deemed-to-satisfy rules stipulated in South African National Standards, rational assessments, and designs by a competent person or performance assessments.

Agrèment SA[4] is a state entity established in terms of the *Agrèment SA Act (Act 11 of 2015)*, with a mandate to undertake performance assessments of construction products for structural strength and stability, fire, thermal and energy, acoustics, and durability. Upon satisfying all the performance requirements, Agrèment SA[4] issues a certificate of 'fit-for-purpose', which summarises the product's expected performance and assures that the product complies with the National Building Regulations[11].

Hartkopf et al.[9] emphasised a connection between performance-based standards and innovation. The performance-based approach in the building industry encourages innovation, allows for more competition, and supports cost-effective building. As such, the South African regulatory environment encourages and promotes innovation in construction. On this basis, this article considers innovative products as those products that have been assessed and certified by Agrèment SA[4] as meeting the performance requirements.

Prospects of 3D construction printing

4IR: 3D printing technology

It has been highlighted that one of the challenges that South Africa faces is the need to provide adequate and affordable housing and accommodation to eradicate the ever-increasing housing backlog. Some of the reasons for the slow pace of delivery include the high cost of construction methods and construction materials, unavailability of raw materials, inexperienced building contractors, and the lack of understanding and appreciation of advances in building technologies. Thus, it has become imperative to evolve a solution to the costliness of building and construction materials and possibly develop viable, cheaper, alternative materials and construction methods that embrace the goals of the Fourth Industrial Revolution (4IR).

The use of 3D printing technologies is a possible solution to provide a cost-saving and fast construction method. Although 3D printing of houses has only started to gain traction in the last few years, the technology was developed in the 1980s by Charles W Hull. Hull patented the first commercial 3D printer or stereolithographic machine in 1986. This machine functioned by having several layers of liquid ultraviolet (UV)-cured resin, one on top of the other, and then using a UV laser to trace and solidify a pattern, which in turn caused each successive layer to adhere to the previous layer. After receiving the first patent, Hull started the company 3D Systems, which commercialised the original rapid prototyping systems for CAD (Computer Aided Design) software.

In recent years, 3D construction printers use a chemically altered concrete mix pumped through a concrete extruder/nozzle controlled in three dimensions.[6] This extruder is controlled by a computerised system and builds the structure layer by layer. Therefore, the key components are (1) a concrete pump, (2) an extruder, and software. The construction process using this technology is thus mainly automated and requires minimal labour.

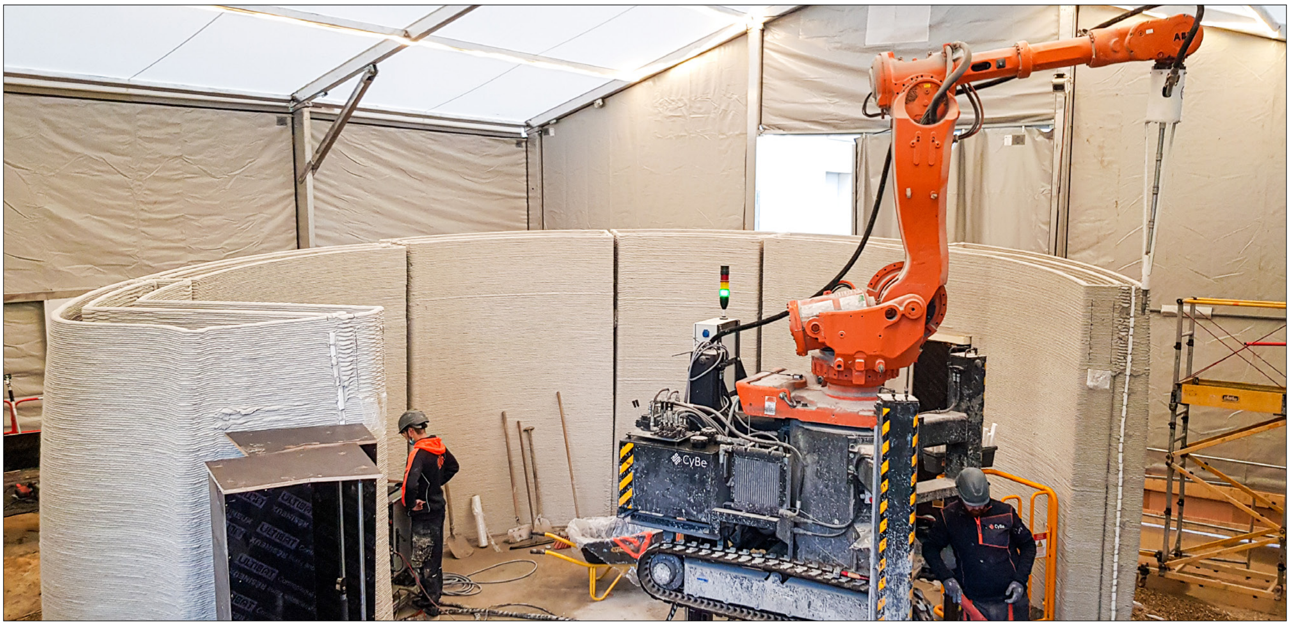
Cement mortar and concrete are composite materials and are the most widely used materials in the construction industry. The primary constituents of mortar and concrete are cement, a fine aggregate (sand), and water. However, these constituent materials have high production costs. In addition, the materials also have a negative impact on the environment during production. For example, Portland cement is obtained from cement clinker produced by heating powdered limestone and clay at a very high temperature. The production of 1 ton of cement is accompanied by the release of 1 ton of carbon dioxide into the atmosphere. Even the quarrying operation involved in the production of quarry dust is energy intensive. In other words, the combination of high-embodied energy and overall environmental recklessness inherent in the production of cement mortar and concrete is an essential consideration in sustainable development. Any measure aimed at reducing the embodied energy mitigates the harm to the environment and reduces the unit cost of concrete/mortar production. Such a measure is, therefore, a sustainable and environmentally friendly alternative to cement and aggregates.

The highlighted problems with traditional aggregates and Portland cement for cement mortar and concrete production necessitate research for alternative, cost-effective binding materials that can partially or wholly replace the traditional construction materials. However, vast quantities of construction, demolition, industrial and agricultural wastes are generated from the activities related to infrastructure development. Due to these huge quantities of waste, disposal is a significant problem in South Africa and worldwide. Hence, instead of landfilling or burning this waste, which may contribute to gas emissions, it could be used as a potential substitute for natural aggregate and cement as a sustainable option for 3D printing production. This will not only convert waste to wealth but also reduce its impact on the environment. However, due consideration needs to be taken when using waste materials to ensure a high-quality and durable design mix. Any contamination in the waste may affect the quality and performance of the printed product.

There are two commonly used systems for 3D construction printer designs, i.e. the gantry-based systems (e.g. COBOD, www.cobod.com) and robotic arm type systems (e.g. Apis-cor, www.apis-cor.com). Both systems have their advantages and disadvantages, depending on the purpose of their applications. The main specifications of a 3D printer are maximum printable area (), extrusion rate (), print speed, and nozzle size (mm). Figure 2 shows an example of a 3D printed walling system and Figure 3 shows a completed 3D printed house.

Potentials for job creation

As mentioned earlier, the government has attempted to address the housing crisis through the scaled delivery of subsidised housing for low-income households. The government policy makes provision for subsidy grants to specific categories of people.



Source: www.cybe.eu/cases

Figure 2: Example of 3D construction printing.

Source: www.cybe.eu/cases

Figure 3: Completed 3D printed house by CYBE.

The Department of Human Settlements launched the Breaking New Ground policy (www.dhs.gov.za) with a vision to:

- accelerate the delivery of housing as a critical strategy for poverty alleviation;
- utilising provision of housing as a significant job creation strategy; and
- leveraging growth in the economy; etc.

A critical question that needs to be answered: is 3D printing of houses going to create job opportunities, as it is perceived that only a few skilled and semi-skilled workers are required to operate the technology during construction? To effectively answer the question, the following needs to be taken into consideration:

- Resources and skills required during construction. Construction of the walling system is possibly about 30% of a completed house. Labour is still required to excavate and prepare platforms, roofing, carpentry, electrical installation, etc. Therefore the role of the community and opportunities for job creation may not necessarily be eroded by using a 3D printer to print the walls.
- Value chain of construction. The value chain for the physical construction of a house begins with identifying materials (e.g. waste), material characterisation and preparation, logistics and delivery to site, construction, and demolition/re-usage. Thus, several job opportunities will be created in the value chain and job creation should be viewed from the perspective of the total value chain cycle and not only the physical construction part.
- 3D printing may be perceived by the youth to be a 'smart' technology. Currently the industry is perceived to be 'dirty', 'dangerous' and 'disorganised'. Hence 3D printing technology has the potential to attract the youth and women to the currently male-dominated industry. With the advancement of technologies, 3D printing will provide a platform for creativity and entrepreneurship development in the house construction industry.

Social acceptability of 3D printed houses

One of the inhibitors in adopting any innovative technology is the challenge of the beneficiaries' social acceptability of the product. However, 3D construction printing technology promises to provide solutions to some of the challenges, notably:

- It is a technology that provides a strong sound structure without the 'knock-on' effects associated with some of the innovative building technologies.
- The technology allows the designers to be creative and produce complex and yet aesthetically pleasing structures (houses) instead of the current 'match-box' houses that have dominated the low-income housing industry. Beneficiaries will therefore have a wider choice of customised housing typologies.

Despite this, there are also challenges that 3D construction printing technology may present for beneficiaries. Challenges include the maintenance of the house should the structure experience any structural distress and re-modelling (additions and alterations) if required. Addressing these challenges may require a combination of conventional and non-conventional techniques and the associated training of the beneficiaries; further research in this area is thus required.

Life cycle costing

Another area of concern in implementing innovative building technologies, including 3D printing, is the cost of construction. Like any new technology, the cost of introducing a new technology is always high due to the required initial high capital outlay. With more uptake and usage of the technology, the costs will decrease, thereby making the product more competitive. Additionally, the cost of 3D printing a house should not be assessed from the construction costs alone. Many advantages, with indirect cost implications, come with the use of 3D printing, which will have the effect of reducing costs if a life cycle cost approach is adopted. The indirect costs considered include:

- faster delivery times;
- usage of waste materials;
- reduction in carbon emissions;
- reduction in energy consumption; and
- reduction of waste on-site.

If all the above factors are considered in the life cycle cost model, it is possible that the 3D construction printing of houses will be much cheaper than the conventional construction.

Benefits of 3D construction printing

Using 3D printing in house construction promises many benefits to the South African housing construction industry, particularly where mass-scale house customisation is required. These can be summarised as follows:

- 3D printing offers high precision and different, complex types of typologies for the end-user. The material mix design offered is consistent, and the integrity of the structure is 'lab-based', giving a structure with the desired structural performance requirements and durability. However, it should be noted that stringent on-site quality assurance is still required to ensure a durable, uniform product.
- Material quantities required for the house construction are controlled and mixed in the right proportions with limited, if any, waste materials.
- The delivery rate is constant (with a possible 24-h production if required) and yet the same quality of production is maintained. Speed of construction has thus a potential of delivering houses much faster.
- As the houses are printed on-site, the logistics and travelling costs are reduced.
- 3D printing house construction has the potential to attract youth and women into the industry.

However, despite the benefits highlighted above, the following considerations would still need to be investigated and addressed:

- Education of professionals, mainly architects and engineers, is required to promote and adopt 3D construction printing technologies. Such education needs to start from tertiary institutions and continue through Continuous Professional Development.
- Effective collaboration is needed between the 3D printing contractor and the professional team.
- High capital outlay is needed for the 3D construction printers.
- Manufacture, of 3D printers that can be used in rugged geographic topographies, particularly in the rural areas, is needed.
- Effective installation of services and rebars (where required) is needed.
- Perceptions of beneficiaries, owners, and government on the performance of houses built through innovative building technologies in general, and 3D construction printing in particular, need to be taken into account.

Recommendations and conclusions

The need to eradicate the housing backlog requires the government of South Africa and the private sector to partner and promote effective and innovative ways of delivering housing. The nature of innovation and the benefits of 3D printing technologies in the complex government housing value chain opens opportunities for mass-scale customisation of houses in South Africa. 3D construction printing has not yet been explored in South Africa, although this technology has been tried and tested internationally.

The conventional 'brick and mortar' home building industry is still highly competitive, although fragmented. It requires low capital and thus makes it easy for new companies to enter and exit the market. As a result, the profit margins are meagre, particularly in the government subsidised housing market. Contractors are reluctant to invest, learn and install any new innovative products.

The government offers limited support to promote construction innovation through technical, finance, or preferential procurement. This is despite government initiatives that go as far back as 2013 when Cabinet Lekgotla resolved to use innovative building technologies to construct social infrastructure. At that time, the Cabinet resolved to set a target of 60% of the specific building types to be constructed from innovative building technologies. To date, no significant investment has been made using innovative building technologies.

To assist the government in the fast delivery of houses using 3D printing technology, further work is still required in the following areas:

- utilisation of waste materials as a cost-effective mix design;
- construction costs vs life cycle costs;
- entrepreneurial development in the value chain of housing delivery as a means to create job opportunities;
- social acceptability of the technology; and
- policy changes to support the implementation of innovative building technologies and 3D construction printing of houses.

The above would need to be verified through comprehensive pragmatic research and practical implementation of the technologies on the ground.

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