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3D Construction Printing – A Review with Contemporary Method of Decarbonisation and Cost Benefit Analysis

Sagheer Ranjha, Ambarish Kulkarni, Jay Sanjayan

Faculty of Science, Engineering and Technology, Swinburne University of Technology, VIC 3122, Australia, sranjha@swin.edu.au, +61 392148369

ABSTRACT

Globally construction industry has highest carbon impacts which accounts for 40% of global energy consumption, 38% of carbon emission as well as 12% of water eutrophication. Thus, there is great demand for decarbonisation in this industry. 3D printing or additive manufacturing has emerged as a potential solution to reduce the energy demands, water wastage and carbon emissions. 3D printing in construction context is an innovative technology that creates 3D objects by reproducing physical objects with continuous layers. Recently, from polymer and steel the industry has leaped forward using concrete with potential applications in the construction engineering. Anecdotally, these technologies proved to reduce production time, minimise wastage and reduce labour costs significantly. The current challenges in 3D printing commercialisation, are lack of standard building codes, large scale investment, functional performance and architectural designs. In this research, concrete prototypes were printed for tests and a comparative study was established with the conventional manufactured concrete to analyse performance standards, cost benefits and lifecycle assessments. Future scope of this research is to develop a performance standards based on benefits for large scale implementation in construction industry.

1. Introduction

The construction industry imposes the highest environmental impacts globally, accounting for more than 40% of global energy consumption, 38% of greenhouse gas emissions and 12% of potable water usage (Comstock et al 2012). However, Comstock (2012) studies indicated that the sector has the potential to significantly cut its resource usage as well as emissions at low costs. According to IPA (2017), Melbourne is the second most expensive city in terms of construction costs, with only New York having greater expenses. The overpriced cost of buildings is inducing the opportunities of innovative construction methods to solve these problems. Over time, additive manufacturing (commonly known as 3D printing) has shown great potential for changing the future of the construction industry.

3D printing attracted enormous amounts of research recently, and part of this is due to its potential within construction industry. 3D printing is technology which creates 3D objects through the production of continuous layers, a process otherwise known as additive manufacturing. The resultant object is designed and modelled using 3D computer-aided drafting software (CAD). When applied to construction, these state-of-the-art machines have the capacity to build far more complex structures at high accuracy, without the help of formwork. As formwork makes up approximately 60% of the materials which assist in the construction of concrete (traditional practices), 3D printing has been proven to save up to 60% of construction waste, 70% of production time and 80% of labour costs (El Sakka & Hamzeh, 2017). Not only can this technology print concrete, it also has the capabilities to print other materials for construction such as polymers, metals and ceramics (Laubier et al. 2018). With the booming of construction industry within Australia and around the globe, 3D printing is looking ever more promising in building houses, bridges and skyscrapers.

Aforementioned, these state-of-the-art machines manufacture by placing materials precisely, significantly reducing resource inputs through structural optimization (As shown in Figure 1). Thus, 3D printers provide promisingly lower energy consumption, as well as reduced emissions & materials. Moreover, additive manufacturing build and customize complex structures without need of supporting structures and formworks, which is not possible with the current conventional methods of construction (De Schutter et al. 2018). Though it has been found the impact of the construction process is negligible in comparison with the material manufacturing process, however, through the structural optimization achieved through 3D printing (Augusti-Juan and Habert, 2016), estimated that additive manufacturing reduces 50% of the environmental impact compared to current traditional methods.

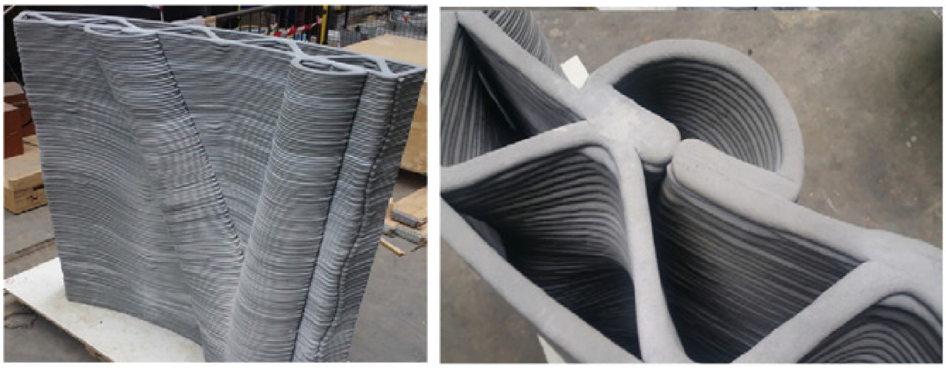

Figure 1: Complex design of 3D printed concrete wall (Gosselin et al. 2016)

With these advancements, large scale construction mere impossible with scope to build 3D printed schools, offices and mass production of houses. For the last few years, many buildings and structures have been 3D printed, showcasing the feasibility of the additive manufacturing for construction industry. Dubai built the world first 3D printed office (Figure 2), a 2,000-square-feet fully-functioned building, in just 17 days and it is now being occupied just as a normal office

(Bridget 2016). A Chinese construction company, WinSun Decoration Design Engineering Co has also printed a five-storey building and a villa in 2015. The two houses were made from steel, cement and construction waste and claimed to meet the standards of construction (Michelle 2015). One of the advantages of the additive manufacturing is the fast time of construction, as WinSun could build 10 houses just in 24 hours (Karyne 2014). As a consequence 3D printing, needs to be studied in context of life cycle, functions and cost benefits in construction industry. This research reviews 3D printing with the contemporary method for decarbonisation and cost benefit analysis.

Figure 2: World first 3D printed office in Dubai

This research project will analyse use existing literature and to discover knowledge gaps and challenges associated with 3D printed construction industry. Possible prototypes of different materials were printed for comparative studies. From data collection, thorough analysis was done using comparisons to traditional practices. In addition, this research studies sustainability of the 3D technology in comparison with existing, conventional methods. Further, a detailed lifecycle analysis was conducted to validate performance standards. Further sections 2 and 3, presents the research methods, cost benefits and lifecycle of 3D printing.

2. Research Methodology

The basic research will be a comparative study comparing 3D construction printing with traditional methods of concrete usage. The method chosen to answer this question will be a case study research which will involve preparing a prototype sample to test and relate back to industry data to prove or disapprove the use of 3D printed concrete in the construction industry. A detailed literature review was done to analyse current state of art in 3D printing context. Duballet et al. (2017), conducted studies on material inputs, material mechanics and the process and implementation was merely focussed. From these studies, it was concluded that additive manufacturing in construction was used in two ways. The first was printing the whole building and other was printing separate components and assemble together later at sites. Based on these studies, it was easier to 3D print whole building if it was simpler and smaller in size. In this method, transportation of the separate parts and the extra labour cost of assembling was eliminated, thus improving costs. The later method was concluded to be suitable for complex, large scale and high rise constructions (Duballet et al. 2017). Printing allowed mass production based cost savings, thus replacing conventional need of moulds and supports for complex shapes. A survey was conducted among civil engineering professionals and “building codes and regulations” was ranked top three of the most influencing factors to adopt the innovative technologies, along with “top management commitment” and “liability for 3D printed components” (Wu 2018).

2.1 3D Concrete Printing Method

For a structure to be 3D printed, first a model has to be built using modelling software or by scanning the structure itself. Then the digital model will be cut into 2D slices and printed accordingly, layer by layer (GuoWei et al. 2016). The technology is feasible to produce more complex structures without need of structures which equates to 40~50% of construction costs. When mass produced 3D printing has advantage of substantially reducing carbon foot prints with additional benefits of time and costs.

2.1.1 Building 3D Model

According to Jeff (2017), there are 7 from CAD software:

1. Build the model as intended from Revit. When done with the model, make it “water-tight” using extrusions, sweeps, and voids. It is considered the most important step to make sure the model is printable.
2. Turn the element layer on to create in-place component/mass visible and make sure the drawing ready for printing.
3. Export the Revit file to STL format so it can be used as input for 3D printer.
4. Use software that is suitable for the 3D printer. In the blog post, Jeff use Cura because it works with his LulzBot Taz 6 printer. There are other software that can be used such as Repetier-Host or Slic3r.
5. Double check the print layers, make sure the model has in-place mass and it is a solid structure.
6. Send to the Printer and press Print.
7. Check the printed prototypes. Sometimes it needs a few trials to get the satisfying printed structure.

2.1.2 Printing Techniques

For print off a prototype for testing, a small 3D printer was used. However, for printing bigger structures, complex structure need bigger printers. To overcome this problem, Khoshnevis (2004) proposed a technology called contour crafting, which improved surface quality, fabrication speed and material input choices. With this 3D printer technology, the complex structures on site were built with the help of crane and robotic arm as illustrated in the Figure 3. Khoshnevis claimed that the contour crafting makes it possible to complete an entire house in the duration of a few hours instead of a few months.

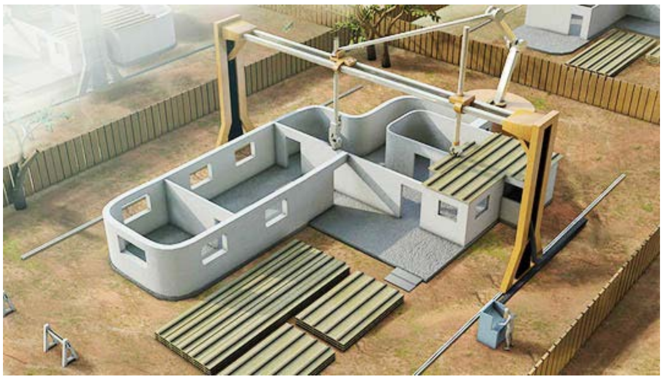

Figure 3: Contour crafting 3D printer (Contour crafting 2018)

A Chinese company, Winsun Decoration Design Engineering Co., did build 10 houses in one day with the help of contour crafting (Levy 2014). The printing method not only saved time, but also reduced the wastage from construction industry. Moreover, contour crafting recycled materials as an input. In addition, the printing machines were based on solar energy to harvest energy consumptions. Therefore, the method was considered eco-friendly exemplar and paved pathway to future of construction industry.

2.2 Prototype Testing and Validation for Performance Standards

This section conducts a study on structures built by the additive manufacturing for lifecycle assessments, a challenge in construction industry. Enormous number of researches are focussed on testing the properties of the 3D printed concretes. Additive manufacturing of concrete properties varies from the conventional methods, as performance of objects were based on layer direction and grain sizes. This implies testing of required functional properties of the structures with applicable buildings standards and codes. Load-bearing capacity, obviously the most important factor that ensures structural performance is a key criteria. Lowke et al. (2018) printed free form structures to measure the density, tensile and compressive strengths at different load direction. Weger et al. (2016) tested the strength and stress capacity of concrete under different conditions. Apart from the load-bearing, other characteristics such as durability, water vapour diffusion resistance, thermal properties and fire-resistant properties plays an important aspect for use in construction industry (Labonnote et al. 2016). The challenges of using 3D printing in constructions identified were: i) structural performance and need of steel enforcement to improve tensile strength and bending movement (e.g.: concrete only provides compressive strength), ii) issues associated with hygroscopic and fluidity of the cement mixture (to be pumped), iii) Hardening and tempering of the concrete layers and the bonds between layers (De Schutter et al. 2018).

Table 1. Mix proportions of the trail mixes (Le et al. 2012)

Material	Mix proportions (kg/m^3)				
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Sand	1612	1485	1362	1241	1123
Cement	376	446	513	579	643
Fly ash	107	127	147	165	184
Silica fume	54	64	73	83	92
Water	150	178	205	232	257

There are many other factors that affect all the above properties of 3D printed cement. The prime one is the cement mixture, the mixture has to be homogeneous to be printable, and different mixture will possess different properties. Weger et al. (2016) varied the permeability of the mixture by mixing different grain sizes of aggregate to check its effect on the properties. Le et al. (2012) tried different mixture ratios as shown in the table 1 to develop the optimum one with 3:2 sand-binder ratio and 70% cement, 20% fly ash and 10% silica fume to produce compressive strength of 110 MPa after 28 days. The surface moisture was found to affect the inner layer-strength, and dry surface lacked bonding between layers (Sanjayan et al. 2018). Zareiyan & Khoshnevis (2017) discovered that the interlocking increased up to 26% of the bonding strength, however other factors such as water content and layer thickness had influence on the properties of the 3D printed structures.

3. Contemporary Methods of Decarbonisation in Construction

The construction sector is one of the most significant contributors of global CO^2 emission outputs, accounting for an estimated 40% of primary energy use within industrialised countries. This includes all stages of a buildings lifecycle in architectural, engineering and construction (AEC), namely the production & operational phases. The manufacturing of construction materials alone (concrete, steel, etc.), account for around 8-12% of total CO2 emissions (Nassen et al. 2007). Effectively, this means the output of carbon during the manufacturing and construction process has quite a significant impact on the surrounding environment, underlining a large importance in reducing carbonisation within construction industry.

Currently, several methods of decarbonisation are being implemented in the construction environment. One prevailing strategy of decarbonisation within the construction sector is to make more of a conscious decision in the materials used within buildings. As shown in Table 2 below, using materials such as timber instead of concrete significantly reduces the output of carbon in the production phase of buildings lifecycle. However, this strategy is often not plausible due to reinforced concrete having far superior properties to that of timber. Not only are the properties of wood inferior, its widespread use in construction brings up other ethical dilemmas such as forestry implications (Buchanan et al. 1994).

Table 2: Carbon emissions produced from common construction materials (Buchanan et al. 1994).

	Carbon Released		Carbon stored	Nett carbon
	$\mathbf{kg/t}$	$\mathbf{kg/m^3}$	$\mathrm{kg/m^3}$	emitted $\mathrm{kg/m^3}$
Treated Timber	44	22	250	228
Glue Laminated Timber	164	82	250	168
Structural Steel	1,070	8,132	15	8,117
Reinforced Concrete	76	182	0	182
Aluminium	2,530	6,325	0	6,325

Another prominent technique to reduce carbon outputs during construction was use of environmentally sustainable concrete. The most popular methods of creating a more sustainable concrete is to either replace the cement content with other materials such as burnt furnace slag & fly ash, or to recycle previously used concrete aggregate (Berndt, 2009). There are currently many mix designs readily available throughout Victoria and Australia, with a vast majority of government funded projects. However, challenge in using these kinds of mix designs were impact on the various structural properties being inferior to regular concrete, thus to use in specific applications (Dumitru, 2000).

These aforementioned methods leap decarbonisation in construction sector, widespread adoption is lagging due to limitations. Hence, this research envisage the critical importance of 3D printing and its impact in decarbonisation of construction industry.

4. 3D Construction Printing Cost Benefit Analysis for Life Cycle Assessment

Large-scale additive manufacturing was considered quite an expensive process, predominantly due to the steep initial set up costs and materials required. Recent advent of materials (e.g. polymers & cement based) has influenced 3D printing technologies as an alternative methods with distinct advantages (Gosselin et al. 2016). It was estimated around 50% of costs using current-day construction methods stem from scaffolding and form work related expenses. This underlines the potential cost saving benefits in addition to minimising carbon impacts in construction industry (Bos et al. 2016). Several studies undertaken compared costs of traditional methods of construction versus additive manufacturing techniques. Buswell et al. demonstrated the cost comparisons plain wall and highly serviced walls (containing various conduits) by printing a concrete. 5.0m x 3.0m wall for a typical house in the UK. These studies concluded, if mass produced the cost capability of 3D printing, with the additive manufactured wall is almost half the cost of a highly serviced wall (Buswell et al. 2007).

There are several types costs associated with the concrete construction, mainly, labour, material and required equipment. Thus in this section these cost analysis were broken down to analyse the impacts. Various studies estimated formwork alone accounted for around 28 – 50% of the costs using traditional construction methods, depended on the construction element. Not only this, formwork also required a significant amount of pre-pour preparation, adding significant CO^2 in the environment (De Schutter et al. 2018). Garcia de Soto et al. (2018) undertook an analysis on the cost breakdown for different kinds of concrete wall construction, as shown in Table 3. This study demonstrated, majority expenses stem from traditional practices, with increased labour for straight walls, and materials (formwork) for curved walls. This was largely due to the preparation of the formwork required in traditional methods.

Table 3: Distribution of labour, material & equipment costs as a percentage for different kinds of concrete wall construction (Garcia de Soto et al. 2018)

Construction Method	Type of Expense		
	Labour	Material	Equipment
Straight Wall / Conventional	56%	23%	21%
Straight Wall / Robot	36%	45%	18%
Curved Wall / Conventional	22%	75%	3%
Curved Wall / Robot	38%	44%	18%

Labour rates are often higher when compared to material costs, with labour accounting for more than 50% of costs in simple conventional concretes. A general in-situ concrete pour often required carpenters, steel fixers, general labourers, operators and cement finishers with high costs (e.g.: minimum of $50AUD per hour). These costs and associated time implies higher construction costs using traditional practices.

The most significant in cost analysis breakdown, dependent on the complexity of the structure. A simple, straight concrete pours rate cheaper formwork utilised, reducing labour costs to $4,009 as shown in the example in Table 4. Whereas constructing complex curvy shapes, adds substantial material costs, resulting 75% of costs using conventional methods. In conclusion, 3D concrete printing was expensive for initial setup and materials used, it deemed useful in certain niche sectors of construction. Leaping forward, as technology productionises with widespread application it provides an alternative sustainable cost effective solution for construction industry (Garcia de Soto et al. 2018).

Table 4: Distribution of labour, material & equipment costs in $USD for different kinds of concrete wall construction (Garcia de Soto et al. 2018).

Construction Method	Type of Cost ($USD)			Total Cost ($USD)
	Labour	Material	Equipment	
Straight Wall / Conventional	$4,009	$1,684	$1,518	$7,211
Straight Wall / Robot	$11,082	$7,808	$3,203	$22,092
Curved Wall / Conventional	$11,941	$41,211	$1,518	$54,669
Curved Wall / Robot	$12,013	$8,043	$3,207	$23,262

In this section cost benefit analysis and comparative study was conducted. The main aim of the cost benefit analysis was to determine returns and relevant benefits of 3D construction printing as shown in Figure 4. The study evaluated highway public-private partnerships and recommended the framework in construction industry (Decorla-Souza et al 2015, p.263). The study provided several steps, the first step was to develop a detailed literature to develop cost model. This included following subsets:

- Planning and preparation
- Procurement
- Design and engineering
- Construction
- Operation and Maintenance
- Systematic risks and uncertainties

A case study with data recorded from previous research was used in this study as second stage. This included determining the benefits of the concrete printing in context of:

- Time savings
- Labour cost savings
- Environmental benefits
- Safety benefits
- Other benefits
- Dis-benefits during construction

Information for safety and environmental benefits were compared to relevant Australian standards and the potential to meet climate change goals such as the Paris 2020 agreement. The third and final step was determining the costs and benefits compared to traditional methods. The criteria developed for the analysis incorporated the triple bottom line analysis as the economic, social and environmental factors playing significant roles. The focus was transferred from traditional cost benefit to socio-environmental factors. After completing the analysis, the results were compared with the results from the engineering plan to provide a complete comparison between the two methods and its effect on the construction industry. These studies indicated current transformation of construction industry requires a leap forward to use these technologies for wide spread adoptions. Bearing challenges with 3D printing limitations, the new paradigm proposes cost benefits and mere impact on environment; an alternative requires testing and establishment of building codes.

5. Conclusions

This research paper reviewed analysed literature and detailed state of art in 3D printing. The comparative study was engaged to examine performance standards of 3D printing with benefits established on costs and environmental impacts. The study concluded challenges impeding wide spread adoption for 3D printers in construction industry. The material performance, bondage, hygroscopic are some limitations of the process. The prime factors such as labour in straight walls and materials in complex curved walls were two cost adding factors in conventional methods. In addition, comparison studies indicated when mass produced 3D printing effectively poses as a viable alternative with cost and environmental benefits.

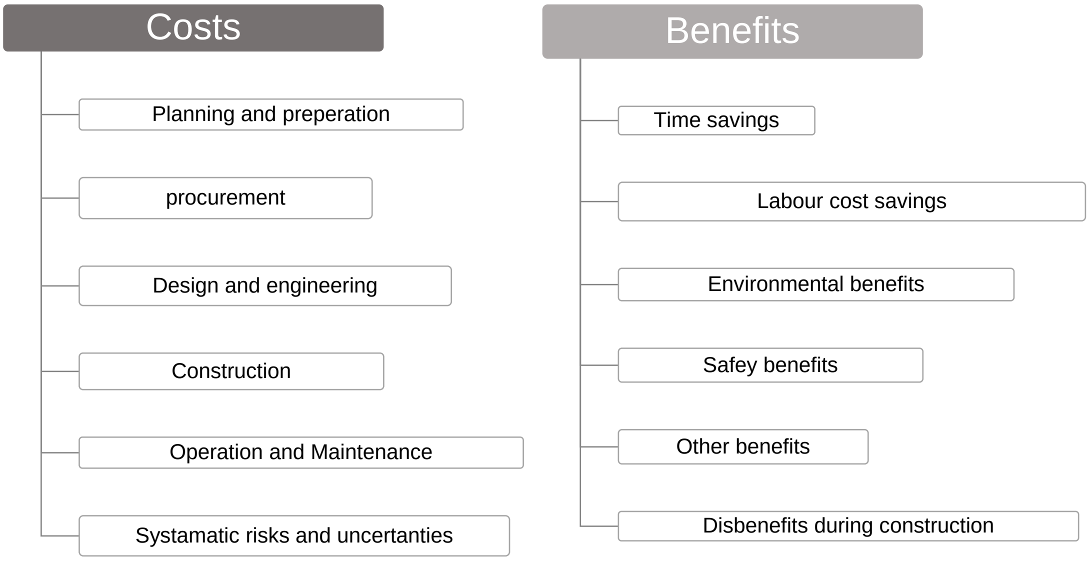

Figure 4: Cost Benefit Analysis Set out

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