PRELIMINARY COST BENEFIT ANALYSIS:

A COST COMPARISON BETWEEN THE THREE-DIMENSIONAL (3D) PRINTING (ADDITIVE) TECHNOLOGIES AND THE CONVENTIONAL BRICK AND MORTAR LOW-COST HOUSING DEVELOPMENTS

Prepared by:

School of Civil Engineering & the Built Environment, University of Johannesburg

For:

National Department of Science and Innovation

Authors: Khululekani **NTAKANA**, Ph.D. Cand, CandQS, CandCPM

Stephen Adeyemi **ALABI**, Ph.D., R. Eng, MNSE

Jeffrey **Mahachi**, PhD

Contents

List of Tables

List of Figures

Executive summary

The Department of Science and Innovation (DSI) has embarked on a programme for the piloting and demonstration of 3D printing additive technologies for sustainable human settlements in South Africa. The DSI has identified 3D printing as a transformative technology that has the potential to revolutionise the housing delivery in the country. The purpose of this programme is to promote, facilitate and finance the technology transfer of environmentally sound and disruptive 3D printing technologies for house construction. Also, to transfer the "know-how" and support the development and enhancement of local capacities and technologies. The piloting and demonstration of these technologies involve 3D printing of at least 50 houses using various architectural typologies. The University of Johannesburg (UJ) has prepared this report as part of the deliverables to perform a comparative cost analysis between 3D printing additive technologies and the conventional building methods (brick and mortar).

Given the extensive social housing backlog in the country, the South African government needs to explore delivery options, including 3D printing, to deliver sustainable human settlements effectively and efficiently. The 3D printing has some advantages, one of these include the time it takes to erect a house. It has been commended that it is quicker to erect than the conventional brick and mortar house construction method. However, two perceived disadvantages of 3D printing were identified: it reduces local labour employment (in number and time) and reduces contribution to the local economy (local material purchasing and local labour employment). Therefore, it becomes imperative to measure the time and cost benefits to determine whether or not 3D printing do offer time and cost benefits. It is also necessary to determine whether 3D printing employs less local labour and whether it has a lesser contribution to the local economy. The main objective of this report is to provide scientific support for adopting 3D printing additive technologies in the delivery of subsidy human settlements as described in the project background.

3D printing will reduce the construction time as compared to the conventional building methods wherein 2 + 2 labourers can take a maximum of two to build just the top structure of a 60 square metre external walls and 31 square metres of internal walls.

Depending on the 3D printing system used and the thickness of the wall, it takes a minimum layout speed of 300mm per second. This would take a minimum of five hours to print the whole walling system of a house. This study, therefore, finds the 3D printing additive technologies as an alternative method to deliver a facility quicker, to a better quality of finish, and at a lower construction cost.

1. Introduction

The University of Johannesburg (UJ) through the School of Civil Engineering and the Built Environment has prepared this report as part of the technical deliverables of the pilot 3D printing of houses, commissioned by the Department of Science and Innovation (DSI). This report seeks to undertake a comparative cost analysis between the conventional brick and mortar building method and the three-dimensional (3D) printing additive technologies to determine whether any benefits occur, where such benefits are located, and whether any further benefits may be possible.

1.1 Project Background

The DSI has embarked on a programme for the piloting and demonstration of 3D printing additive technologies for sustainable human settlements in South Africa. The DSI has identified 3D printing as a transformative technology that has the potential to revolutionise the housing delivery in the country. The purpose of this programme is to promote, facilitate and finance the technology transfer of environmentally sound and disruptive 3D printing technologies for house construction. Also, to transfer the "know-how" and support the development and enhancement of local capacities and technologies. The piloting and demonstration of these technologies involve 3D printing of at least 50 houses using various architectural typologies. In determining which additive technology to pilot, the UJ established essential criteria according to which technology should be evaluated to assess if it is as good as or better than the conventional brick and mortar house construction method. These criteria are:

- Faster speed of erection;
- Lower cost of construction;
- Ease of maintenance;
- Job creation potential; and
- Compliance with the National Building Regulations, South African National Standards, National Home Builder's Registration Council, and Agrèment South Africa.

1.2 Department of Science and Innovation

The University of Johannesburg’s collaborator and funder for the project.

1.3 University of Johannesburg

The research team in collaboration with the DSI.

2 Background to Life Cycle Costing

UJ has made other reports to DSI wherein recommendations on the application of 3D printing additive technologies in South Africa have been proposed. One of these reports is on the "Availability of 3D printers", and identifies internationally available 3D printers, and makes a detailed cost and functional performance comparisons. One of the advantages of 3D printing as identified in the reports is that the 3D printing provides for quicker construction than the conventional "brick-and-mortar" house construction method. Given the extensive social housing backlog in the country, the South African government needs to explore innovative options, including 3D printing, to deliver sustainable human settlements effectively and efficiently.

Those reports further highlight two perceived disadvantages of 3D printing to be reduced local labour employment (in number and time), and reduced contribution to the local economy (local material purchasing and local labour employment). Therefore, it becomes imperative to measure the time and cost benefits to determine whether 3D printing does offer time and cost benefits. It is also necessary to determine the extent to which local labour is used in 3D printing and its contribution to the growth of the local economy.

2.1 Purpose Statement

A quantitative analysis and evaluation of the cost and time benefit, the labour contribution, and the local economic contribution of the 3D printing additive technologies compared to the conventional brick and mortar house construction method based on the final account of the pilot project. Furthermore, determine the benefits, if any, where these benefits are located in the construction process, and where additional benefits may be found (i.e. whole life cycle costing analysis).

2.2 Objective and Purpose of the Cost Comparison

The main objective of this report is to provide scientific evidence in support of the adoption of 3D printing additive technologies in the delivery of subsidy human settlements as described in the project background. The outcome of this report will be a quantifiable result that shows the extent of 3D printing cost and time benefit, local labour contribution and the local economic contribution compared to conventional brick and mortar house construction. The sub-objectives of this report are:

- To develop a benchmark for comparing building methods;
- To weigh investment opportunities in 3D printing (additive) technologies;
- To measure social benefits; and
- To develop reasonable conclusions around the feasibility and/or advisability of building methods.

2.3 Scope of Work

The scope of work was limited to a standard 40 square meter housing subsidy quantum published by the department of human settlements as of April 2018. This was conducted to demonstrate the performance of 3D printing over the conventional "brick-and-mortar" house construction method.

- Auditing the final account for time and cost benefits to the client;
- Identifying the areas in which time and cost benefits are located in the project;
- Analyse any potential further time and cost benefits in the project;
- Analyse local labour employment;
- Analyse local economic contribution; and
- Capturing the findings

2.4 Definitions

For this report, the following definitions will apply:

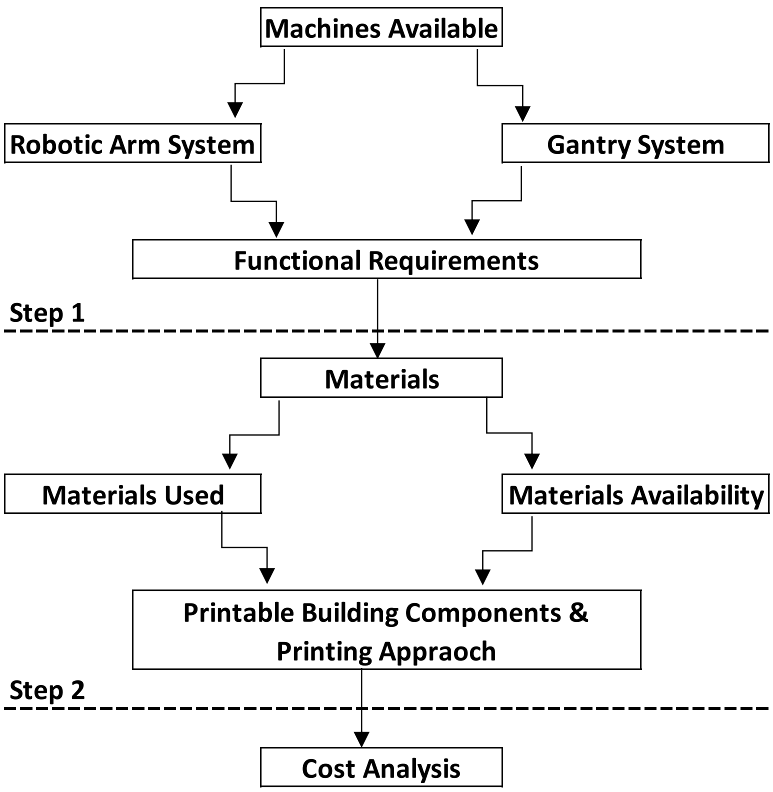
- **3D Printing Additive Technologies:** a Computer-Aided Design (CAD) to create three-dimensional objects through layering materials such as plastics, composites or biomaterials to create objects that range in shape, size, rigidity, and colour.
- **Cost Centres:** meaning those components of the construction project as typically described in the original Bills of Quantities (BoQ).

- **Final Account:** means a conclusion of the construction contract sum (including all necessary adjustments) and signifies the agreed amount that the employer will pay the contractor.
- **Final Summary:** means the summary of all the costs projected for the construction project including builder's work, preliminaries, provisional sums, prime costs sums, contingencies, and VAT.

3 Methodology

This is a preliminary quantitative desktop study to determine the cost savings for a pilot 3D printing project. In one of the reports prepared by the UJ (machines availability report), for the DSI, two systems of 3D printing technologies were identified (Robotic arm system and Gantry system). As presented in **figure 3.1** below, the first step in this research report was to understand the functionality of these two systems, the materials used to print houses, and the availability of these materials locally. The second step was to analyse which building components can these two systems print and the manner or systemic approach to be adopted in printing the houses. In the machines availability report, it was identified that these systems considering the availability of the material in the country and the level at which this pilot project is, only the walls could be printed. Therefore, in this step, the analysis of the cost centres was conducted on the comparative bases with the conventional brick and mortar house construction method. An attempt will be made to evaluate if other building components could also be printed.

Table 3.1: The Methodological Approach



The conventional structure of the Bills of Quantities (BoQ) was used. This BoQ as presented in **table 3.1** below includes the Preliminary and General, Foundations to Surface Beds, superstructure (top structure or walls up to wallplate level including gable ends), Roofs (structure and covering), Plumbing (including rainwater goods), Doors and Windows (including frames, finishes and glazing), Wall and Floor finishes, and Electrical installation. Lastly, the third step was to collect and collate the data and interpret the results.

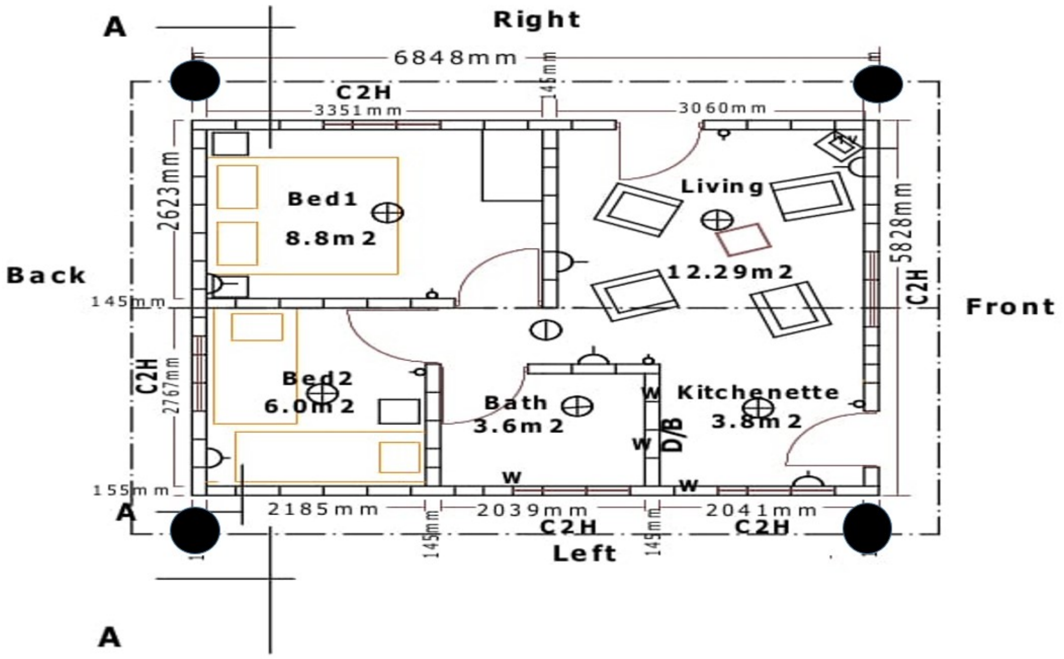
Table 3.1: Standard Bills of Quantities for a low-income house

Description	
Milestone 1: Foundations	
Milestone 2: Wallplates	
Milestone 3: Roofing	
Milestone 4: Rain Water Goods	
Milestone 5: Electrical	
Milestone 6: Ceiling	
Milestone 7: Painting	
Milestone 8: Aprons	
Milestone 9: Plaster	
Milestone 10: Doors	
Milestone 11: VIPToilet	

3.1 Typologies considered

A standard subsidy house plan was selected for this study. It is a 40 square meter house with two bedrooms, one bathroom, a living area, and a kitchenette as shown in figure 3.2 below.

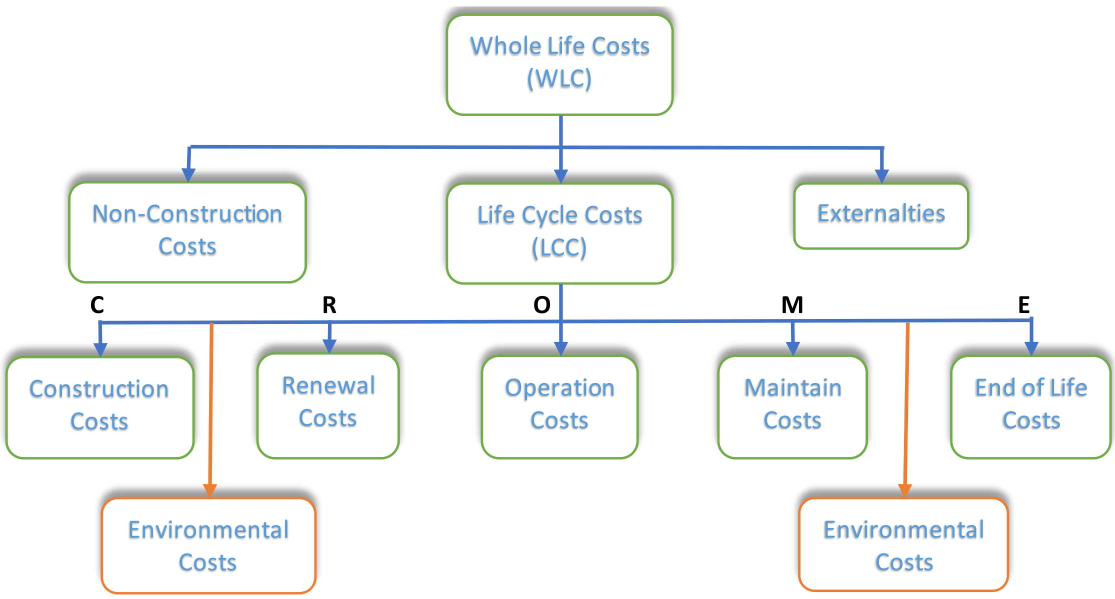
Figure 3.1: Typical subsidy house floor plan



3.2 Life Cycle Costing Plan Structure

A common life cycle cost (LCC) plan structure is employed and the benefit of using such is in the standard presentation understood by clients and professionals alike, and in the easy comparison and benchmarking of similar projects. A conceptual plan structure employed for this LCC is presented in **figure 3.3** below.

Figure 3.2: The Preliminary LCC Plan Structure



The scope of costs to be included under the above cost centres should be explicit and agreed with the DSI. The above cost centres will include preliminary costs as follows:

- **Non-construction costs:** costs associated with land acquisition, fees, relevant liabilities, etc.)
- **Externalities:** costs associated with an asset but not reflected in the transaction costs of the acquisition (i.e. a new water main), so a cost is incurred but not by the client or contractor.
- **Construction costs:** these include site costs or opportunity costs of the site already in ownership (i.e. legal fees, stamp duty, etc. – not site acquisition costs). Finance charges; professional fees; construction costs; tax allowances (capital equipment allowance, capital gains, corporation tax, etc.); statutory charges; development grants planning gain; and third party costs (i.e. right of light, over sailing charges, wayleaves and easement, etc.).
- **Environmental costs:** costs associated with recycling, carbon emissions, renewable energy, etc. These costs may occur before and during construction, and before and during disposal of an asset.
- **Operation costs:** Often referred to as soft facilities management costs; commonly interpreted to mean all costs incurred in running and managing the facility (i.e. rates and other local taxes, waste management, insurances, energy efficiency, etc.).
- **Maintenance costs** (split into renewal and maintain costs): often referred to as hard facilities management costs; commonly interpreted to mean all costs incurred in ensuring the continued specified functional performance of the asset (i.e. redecoration, periodic inspection activity, periodic maintenance and component replacement activities, etc.).
- **End of life costs:** This specifically includes disposal and demolition costs.

Some of the above costs are not included in this LCC. This is a preliminary LCC, once the project has been piloted and all costs identified a final LCC will be conducted and even the plan structure may be revised.

3.3 Comparative Cost Analysis

There are different South African National Building Regulations performance requirements for building systems to be regarded as safe, appropriate and efficient. These relate to climate, materials availability, skills availability, building standards and social acceptability. The performance of the 3D printed government subsidy houses should therefore be assessed in the South African context before rigorous evaluation and analysis. In this report, the design, delivery and erection of these houses are discussed together with its subsequent evaluation. Both the design and its constructability are assessed for South African conditions.

3.4 Pilot Project

Because this is a preliminary comparative cost-benefit analysis, the UJ has not yet undertaken the construction of the 50 houses as indicated in **section 2.1** above. A housing subsidy quantum published by the department of human settlements (DHS) was used. There are three subsidy categories offered by the DHS, notably standard 40 square meter dwelling, 45 square meter dwelling for disabled persons, and 50 square meter dwelling for military veterans. A subsidy quantum for a standard 40 square meter dwelling, as at April 01, 2018**,** was used to analyse the results for the value proposition of the 3DCP as depicted in **table 3.2** below.

Table 3.2: Final Summary of the conventional brick and mortar building method

Housing Subsidy Quantum (with no variations)		
	Targeted Unit Cost	**Total Amount**
Contract Value	107,825.08	5,391,254.00
P&G Amount	9,041.92	452,096.00
	116,867.00	**R 5,843,350.00**
CONVENTIONAL COSTS OF CONSTRUCTION		
Foundations	30,129.58	1,506,478.75
Wall Plates\ Blockwork	23,414.03	1,170,701.30
Roofing	15,951.01	797,550.50
Finishes	21,934.64	1,096,731.98
Electrical	4,666.26	233,313.00
VIP Toilet	7,938.23	396,911.50
Tank Stand & Rain Water Goods	4,973.17	248,658.50
Sub-Total	**109,006.91**	**5,450,345.53**

From the table above, it is evident that the housing subsidy quantum (construction costs only) including all preliminaries and general (P&Gs) is **R116, 867.00**. Taking into consideration the building materials costs plus labour calculated, as at 2020/21 financial year, the construction costs would be **R109, 006.91**. The difference between these two costs is the costs of project management, clerk of works, transfer costs, and beneficiary administration.

3.5 Standard Bills of Quantities

There are different pricing methods for a construction project. Generally, contractors' price includes, unless otherwise stated, materials, labour, plant, taxes, overheads and profits. However, construction costs are located in three main cost centres, namely preliminaries and general, materials and labour. In pricing the BoQ, the contractor is required to fill in a chargeable rate next to the quantity of work to be done as stipulated in the BoQ. The price of the work will be determined by multiplying the quantity by the rate stipulated by the contractor. That rate will include the associated preliminaries and general, materials, and labour costs. The BoQ is structured per the various components of the building, commencing with the foundations/substructure and progressing through superstructure, roof assembly, services, finishes, and external works. The following sections identify those building components in detail to evaluate where 3D printing costs savings might accrue.

3.5.1 Preliminaries and General

Preliminaries include site establishment by the contractor, site management, etc. in price this section of the BoQ, contractors are required to price the relevant items of that particular project individually. The extent of administrative costs involved is directly related to the duration of the project: the longer the contractor has to maintain an office on-site, the greater the costs of preliminaries. In terms of 3D printing, the assembling and calibrating of the machines before printing takes places and later dismantling and cleaning of the machine will have to be taken into consideration. Other costs, which are not necessarily preliminaries that will later have to be adjusted in the final account of the project, include provisional sum and prime cost sums. These are amounts placed in the BoQ to cover work that may either be specialist or not fully documented at the time of tender.

Also, budgetary allowances cover profits, attendance of nominated or selected subcontractors, taking delivery on-site work executed under a separate contract, coordination, and the number of selected or nominated subcontractors. With the time that is expected for the 3D machines to print a house, it is also expected that most cost savings will accrue in the cost centre.

3.5.2 Substructure / Foundations

For any building project, the substructure includes any associated earthworks, concrete, formwork, reinforcement, masonry, and waterproofing. Depending on the nature of the soil to which the house is built, for most low-income housing stock in South Africa, a raft foundation is normally used. This type of foundation consists of concrete, formwork, reinforcement, and waterproof, and is very much possible to print it. Concrete is expensive compared to the additives used for 3D printing. Therefore, costs savings will also accrue in this cost centre as well. Strip foundation is another type of foundation that could be used for low-income housing which consists of concrete, formwork, reinforcement, waterproofing, and masonry. In future, if this type of foundation is printed, costs savings may accrue as well.

3.5.3 Superstructure

The superstructure includes walls from finish floor level to wallplate height including the gable ends. Most 3D printing projects have been tested on this very simple building component. Research reveals that most 3D printing machines can only print the walling system. There is a need to investigate and validate whether there are other building components that could be printed as well.

3.5.4 Roof Construction

Roof construction includes roof structure (trusses whether steel or timber, purlins or battens, and braces), roof covering (roof tiles or corrugated iron), and rainwater goods (fascia boards, barge boards, gutters and downpipes). The latter are conventional building methods of roof construction.

3.5.5 Doors and Windows

Doors and windows include all materials (timber, aluminium or steel) used internally and externally, metalwork (door and window frames), and ironmongery. For windows, if steel frames are used, glazing is included. No savings will accrue in this building component, these are fittings only after the walls and the roof have been printed.

3.5.6 Finishes

Depending on the type of finish required (as per the architectural specification), these include plastering (internal and external), screed to floors, tiling (floors and walls), paintwork (internal and external), and ceilings (including all necessary fittings). Most 3D printed houses do not necessarily require finishes; costs may be saved in some or all of these building components.

3.5.7 Plumbing

Plumbing includes piping and sanitary fittings. The labour-intensive time benefit could accrue from this building component, for example, the piping could be placed in position before printing takes place thus reducing the cost of chasing walls. Chasing has a potential negative effect of affecting the structural integrity of the building.

3.5.8 Electrical Installations

An electrical installation includes conduits, fittings, distribution boards, etc. Similar to the above building component, costs savings would accrue from avoiding chasing the walls for conduits.

4 Life Cycle Costing: Option Appraisal

4.1 Construction Costs

For this analysis, as reported in the “Printer Availability Report”, two 3D printing systems are compared to the conventional building methods separately. However, both these 3D systems can only print the walls (milestone 2 in **Table 4.1**). It is not possible, for now, to extract the labour contribution at each cost centre as the BoQ calls for a rate per unit in each cost centre and that rate includes labour, materials and overheads and profits.

4.1.1 Robotic Arm System

Typically, a robotic arm system is placed on a vertical metal frame, which is anchored to the surface (Apis-cor, 2019). The robotic arm is attached to a hose, which carries the concrete from the reservoir to the nozzle. The robotic arm then moves the nozzle to the programmed positions. Figure 6.1 below depicts a typical robotic arm system.

Figure 4.1: Robotic Arm System

Source: Apis-cor website, 2019

Depicted below in **table 5.1** is the comparative cost for each cost centre as described in **section 5** above. For purposes of this analysis, the numbers in the table have been rounded up or down as the case may be.

Table 4.1: Cost Comparison for Robotic Arm System

COST OF CONSTRUCTION	CONVENTIONAL	ROBOTIC ARM	% SAVINGS
Foundations	30,129.58	30,129.58	**0.00%**
Wall Plates\ Blockwork	23,414.03	22,088.36	**5.66%**
Roofing	15,951.01	15,951.01	**0.00%**
Finishes	21,934.64	21,934.64	**0.00%**
Electrical	4,666.26	4,666.26	**0.00%**
VIP Toilet	7,938.23	7,938.23	**0.00%**
Tank Stand & Rain Water Goods	4,973.17	4,973.17	**0.00%**
Sub-Total	**109,006.91**	**107,681.24**	**1.22%**

The building costs in this particular case scenario, including all cost centres as depicted in the table above, are **R107, 681.24** excluding VAT for the robotic arm system and **R109,006.91** excluding VAT for conventional building methods. This indicates a construction cost-benefit of **1.22%** when printing the house as compared to the conventional building methods. This comparison is conducted only in one cost centre (walls). It is expensive to set up a machine and print just walls of a 40 square meter house. There needs to be, a future investigation, on the applicability of 3D printing for other cost centres (i.e. foundations, roofs, tank stands, etc.).

4.1.2 Gantry System

The gantry system consists of a structure, designed using standard steel profiles. The base of the gantry printer is usually a standard universal beam, flat steel base or an isolated steel base on which a rail is welded for the horizontal movement of the printer assembly. The printing head assembly is mounted on linear bearings to provide vertical movement of the head assembly. The printing head hangs from gliders to provide the horizontal movement of the printing head. The flexible hose for the printing material is also connected to the glider system to provide easy movement. **Figure 4.2** below depicts the gantry system:

Figure 4.2: Gantry System

Source: COBOD website, 2019

Depicted below in **table 5.2** is the comparative cost for each cost centre as described in **section 5** above. For purposes of this analysis, the numbers in the table have been rounded up or down as the case may be.

Table 4.2: Cost Comparison for Gantry System

COST OF CONSTRUCTION	CONVENTIONAL	GANTRY	% SAVINGS
Foundations	30,129.58	30,129.58	**0.00%**
Wall Plates\ Blockwork	23,414.03	21,091.36	**9.92%**
Roofing	15,951.01	15,951.01	**0.00%**
Finishes	21,934.64	21,934.64	**0.00%**
Electrical	4,666.26	4,666.26	**0.00%**
VIP Toilet	7,938.23	7,938.23	**0.00%**
Tank Stand & Rain Water Goods	4,973.17	4,973.17	**0.00%**
Sub-Total	**109,006.91**	**106,684.24**	**2.13%**

The building costs in this particular case scenario, including all cost centres as depicted in the table above, are **R106,684.24** excluding VAT for the gantry system and

R109,006.91 excluding VAT for conventional building methods. This indicates a construction cost-benefit of **2.13%** when printing the house as compared to the conventional building methods. This comparison is conducted only in one cost centre (walls).

4.2 Local Economic Contribution

The construction sector is one of the biggest employing industries in South Africa thus contributing to the nation's Gross Domestic Product (GDP). The industry employs over 8% of the country's labour force and construction output accounts for around 4% of the country's GDP. Construction activity usually delivers site benefits including the employment of local labour and the local purchasing of construction materials. Conventional building methods tend to leave a larger local economic empowerment in terms of local labour employment and local purchasing of construction materials particularly those materials that have a significant transport implication such as fine aggregates, cement, bricks and timber.

4.2.1 Material Purchasing

3D printing additive technologies generally use different compositions of materials range from industrial (glass, slag, etc.), agricultural (rice husk ash and fly ash) as well as construction and demolition (recycled masonry) wastes. Printing can produce multiple components simultaneously using both conventional and recycled materials and can use multiple colours. Some techniques include the use of dissolvable materials that support overhanging features during construction. Some of the machines have material flexibility; therefore, locally sourced material designs can be used. Others only use prescribed materials as per the manufacturers' pre-packaged mix designs. The pre-packaged materials only require the addition of sand, Portland cement and water. Most of these materials and the labour required can generally be sourced closer to the factory, which at times may be located far away from the construction site.

Under these conditions, the employment of labour and the purchasing of materials will be split between the geographic position of the factory and the construction site (the degree of the split will be dependent of the type of printer employed). Therefore, the quantum of the local economic contribution will be influenced by the location of the construction site. In remote areas, for example, materials may not be readily available requiring that it be procured at the nearest centre likely to have such materials.

4.2.2 Labour

The construction sector is commonly known of employing workers with relatively low skill levels and that is capable of providing income only for the duration of the construction project. Construction projects in areas where economic activities are constrained or limited are capable of providing some level of employment even though it might be for a limited duration. In this case, local skills are developed thus improving future opportunities for the local labour. 3D printing additive technologies cover a variety of construction methods ranging from intensive on-site printing to off-site printing (e.g. printing modules/panels). On-site printing only requires two people (MudBots, 2019) to operate the machine and two unskilled labourers to feed the concrete mixer. For the human settlement development, 2 bricklayers and 2 unskilled labourers are required to build the top structure of one 40 square metre house. This does not necessarily reduce the number of local skills required as compared to the conventional brick and mortar construction methods but introduces a different type of skill required for construction.

Nevertheless, the contemporary trend in construction globally is moving toward off-site construction. The reason for this is that quality control is better when working under a controlled environment, and working conditions are better (occupational health and safety) compared to on-site construction. The shift from on-site to off-site employment has obvious implications on the construction labour market such as off-site (factory-based) employment is perceived as decent employment as the working conditions are safer and more comfortable than those found on-site are. This is despite that some people prefer working on-site than in a controlled environment. Furthermore, factory-based tends to be more permanent compared to on-site employment. For example, a factory-based printer can produce modules for assembly anywhere in the country for as long as there is a market demand for such products. This is in contrary to on-site employment which tends to be project-specific and employees are subject to termination at the end of the contract. Also, these kinds of employment tend to up-skill employees since the printing of modules is more closely related to the manufacturing industry than the construction industry.

Data will be collected from the pilot project to determine the following:

- The value of the construction cost spent on local labour. Depending on the type of the 3D printing system used, a portion of the top structure value can also be used on local labour (i.e. plastering and painting); and
- The quantum of the value spent on local labour can also be influenced by the location of the construction project.

4.2.3 Impact of time

In any construction project, it is well known that the basic project parameters are time, cost, and quality. **Table 5.3** presents a comparison of the three-building alternatives, i.e. conventional, robotic arm and the gantry system. However, it is of importance that to highlight that for 3DCP the material, labour, and machine costs used in the below table are provisional (company based rates). Once local materials have been identified and implemented in the pilot project, costs will be analysed and audited.

Table 4.3: A comparison of the basic project parameters

Technology	Material required (kg)	Delivery time (h)	Material (costs/m2)	Labour (costs/m2)	Equipment/machine (costs/m2)	Total (costs/m2)
Brick and mortar	25 760	16	R 140	R 81	R 17	R 238
Robotic arm system	23 000	15.5	R 108	R 11	R 80	R 199
Gantry System	19 920	12	R 108	R 18	R 60	R 186

4.3 Analysis and calculations

4.3.1 Key Variables

The life cycle costs of the 3D printed houses have been analysed using the following key variables:

- The period of analysis: 30 Years (typically decided by the client);

- The interest rate for future costs: 11.5% (representing either the cost of borrowing or the loss of alternative investment for private clients);
- The discount rate: between 1% and 5% (representing either the cost of borrowing or the loss of alternative investment for private clients);
- The cycles or intervals between maintenance activities (typically based on analysis);
- The unit rates for work to be done (typically based on analysis).

4.3.2 Sensitivity and Risk Analysis

Sensitivity has been analysed to manage risk in the whole life cycle of 3D printed house. In this context, it is primarily changing the variables, for example, the LCC period of analysis, and the interest rates. Variations in the discount rate are analysed by 'what if?' questioning of the results by changing the discount rate based on real time costs for a conventional building method as depicted in **table 5.4** below.

Table 4.4: Changing discount rate based on real time costs - Conventional

Cost heading	Year in which cost occur	Expected yearly cost	Discount factors for 1%	NPV 1%	Discount factors for 3%	NPV 3%	Discount factors for 5%	NPV 5%
Wallplate	1	23,414.03	0.9901	23,182.00	0.9709	22,732.00	0.9524	22,299.00
Painting	5	4,269.47	0.9515	4,062.00	0.8626	3,682.00	0.7835	3,345.00
Rain Water Goods	10	4,973.17	0.9053	4,502.00	0.7441	3,700.00	0.6139	3,053.00
Painting	10	4,269.47	0.9053	3,865.00	0.7441	3,176.00	0.6139	2,621.00
Apron	15	3,990.44	0.8613	3,437.00	0.6419	2,561.00	0.4810	1,919.00
Painting	15	4,269.47	0.8613	3,677.00	0.6419	2,740.00	0.4810	2,053.00
Doors	20	4,227.98	0.8195	3,465.00	0.5537	2,340.00	0.3769	1,593.00
Painting	20	4,269.47	0.8195	3,499.00	0.5537	2,363.00	0.3769	1,609.00
Painting	25	4,269.47	0.7798	3,329.00	0.4776	2,039.00	0.2953	1,260.00
Total NPV		**57,952.96**	-	**53,018.00**	-	**45,333.00**	-	**39,752.00**

The discount factors are the annual discount rate used in the equations to represent the cumulative percentage rate chosen for discounting. Therefore, for example, 3%p.a. discount rate produces a first-year discount factor of **0.9709**. By year 10, the total discount factor is **0.7441**, by year 20 it **is 0.5537**. The total net present value of the expected future costs on 3D printed houses at 3% discount rate in varying cycles using the base case is **R45,333.00** per unit. However, these costs could be compounded by the borrowing rate into the future and then discounted back to today's costs. **Table 4.5** below presents the sensitivity analysis with compounded future costs by 11.5% annual borrowing rate.

Table 4.5: Sensitivity analysis with compounded future costs - Conventional

Cost heading	Year in which cost occur	Expected yearly cost	Discount factors for 1%	NPV 1%	Discount factors for 3%	NPV 3%	Discount factors for 5%	NPV 5%
Wallplate	1	23,414.03	0.9901	23,182.00	0.9709	22,732.00	0.9524	22,299.00
Painting	5	6,724.41	0.9515	6,398.00	0.8626	5,800.00	0.7835	5,268.00
Rain Water Goods	10	12,336.57	0.9053	11,168.00	0.7441	9,179.00	0.6139	7,573.00
Painting	10	10,590.95	0.9053	9,587.00	0.7441	7,880.00	0.6139	6,501.00
Apron	15	15,590.59	0.8613	13,428.00	0.6419	10,007.00	0.4810	7,499.00
Painting	15	16,680.75	0.8613	14,367.00	0.6419	10,706.00	0.4810	8,023.00
Doors	20	26,016.88	0.8195	21,321.00	0.5537	14,404.00	0.3769	9,805.00
Painting	20	26,272.18	0.8195	21,531.00	0.5537	14,546.00	0.3769	9,901.00
Rain Water Goods	20	30,602.40	0.8195	25,080.00	0.5537	16,943.00	0.3769	11,533.00
Painting	25	41,378.69	0.7798	32,265.00	0.4776	19,762.00	0.2953	12,219.00
Total NPV		**209,607.45**	-	**178,327.00**	-	**131,959.00**	-	**100,621.00**

The total net present value of the compounded future costs on 3D printed houses at 3% discount rate in varying cycles is **R131,959.00** per unit. This is based on the common estimated service life of cost centres. However, **table 5.6** below depicts the total NPV based on the optimistic and pessimistic estimated service life.

Table 4.6: Optimistic and pessimistic estimated service life (ESL) - Conventional

Cost heading	Year in which cost occur (base case)	Expected yearly cost	Cumulative Cost		
			Base Case	Optimistic ESL	Pessimistic ESL
Wallplate	1	23,414.03	23,414.03	23,414.03	23,414.03
Painting	5	6,724.41	4,269.47	7,497.72	5,951.11
Rain Water Goods	10	12,336.57	4,973.17	15,173.98	9,499.16
Apron	15	15,590.59	3,990.44	20,969.34	10,211.83
Doors	20	26,016.88	4,227.98	37,984.64	14,049.11
Total NPV			**40,875.09**	**105,039.71**	**63,125.24**

Estimated services lives are increased and decreased by 20%, and rounded to the nearest year. The interest of the decreased or increased ESL is calculated and added or subtracted from the base case to arrive at the optimistic or pessimistic ESL. For example, ESL of painting is 5 years at projected costs of **R6,724.41**. Optimists would increase this ESL by 20% and round it to the nearest year (6 years ESL) thus increasing costs to **R7,497.72**. However, for pessimists ESL is decreased to 4 years thus decreasing costs to **R5,951.11**. Therefore the total NPV for optimists is **R105,039.71** and for pessimists is **R63,125.24**.

4.3.3 LCC Findings

The calculations of the LCC are summarised in **table 4.7** below.

Table 4.7: LCC optional appraisal summary

LCC OPTIONAL APPRAISAL	CONVENTIONAL		ROBOTIC ARM		GANTRY SYSTEM	
	per unit	50 units	per unit	50 units	per unit	50 units
Total Life Cycle Cost (Present Worth)	701,317.00	35,065,850.00	679,779.00	33,988,950.00	672,512.00	33,625,600.00
Life Cycle (Cost)/Savings to Baseline			21,539.00	1,076,950.00	28,806.00	1,440,300.00
LEAST LIFE CYCLE COST (YES/NO)	NO		NO		YES	

The identified life cycle cost/saving to the base case at present worth per unit is **R28,806.00** if gantry system is used to print the houses. A total of **R1,440,300.00** for 50 units can be seen as cost-benefit to the client after the pilot study. These are preliminary estimates, of course not taking into account other factors such as manufacturing additives locally which will reduce drastically the cost of printing particularly using the robotic arm system. The table above depicts a cost-benefit of **R21,539.00** per unit life cycle cost to the client if the robotic arm system is to be used, amounting to **R1,076,950.00** for 50 units.

4.3.4 Terminal and residual values

Terminal values: represent the scrap value of a system or component that fails during the LCC period of analysis. For example, the replacement of lead flashings should take into account the scrap value of the lead, which is included in the LCC calculation as a terminal value. Residual values: represent the value of an asset at the end of the period of study. The common method of determining the residual value is based on the straight-line method of depreciation.

4.3.5 Post-Occupancy

At this stage, data will be made available, against which the accuracy of the LCC predictions can be measured. LCC audits will be conducted at predetermined intervals, and reported with other performance aspects of the building, in a post-occupancy evaluation report. Additionally, any changes to the building will be assessed and reported using the measures of economic performance to enhance the reporting data (i.e. actual energy consumption is typically monitored against estimated energy consumption).

4.3.6 Sustainability and Energy Efficiency Assessment

Methodologies such as BREEAM and LEED introduce the desirability for an LCC calculation to support decisions on new and refurbishment projects taken with respect to sustainability. The LCC can only support an appreciation of economic aspects of sustainable design that are quantitative. If any non-quantitative aspects are given a notional quantitative value (e.g. disruption to traffic flows or health impacts) should be identified separately and kept out of the basic calculation.

5 Conclusions

Depending on the 3D printing system used and the thickness of the wall, it takes a minimum layout speed of 300mm per second. This would take a minimum of five hours to print the whole house. There is a preliminary evidence that 3D printing might reduce the construction time as compared to the conventional building methods wherein 2 + 2 labourers can take a day or two to build the top structure of a 60 square metres external walls and 31 square metres of internal walls. From the life cycle costing analysis conducted, the following findings were established:

I. There is preliminary evidence to substantiate that 3D printing additive technologies are a cheaper building method than their conventional counterpart;
II. The exact quantum of the savings is dependent on the type of system used and the location at which it is used;
III. Allocating the savings in a direct comparative way can be a challenge due to the pricing structure of the 3D printing system (a system is priced rather than a collection of parts);
IV. Because the systems can only print walls, savings seem to occur only at two cost centres (walls and preliminaries and general). The effect of the impact of time still needs to be investigated.
V. A preliminary judgement could be made that the biggest contributor to the overall savings is a reduction in construction time resulting in savings from P&Gs.

This study, therefore, finds the 3D printing additive technologies as an alternative method to deliver a facility quicker, to a better quality of finish, and at a lower construction cost. However, data will be collected during the pilot project to determine the above in more detailed and satisfactory manner to the DSI. Going forward, data will be collected during the pilot project of 50 houses to determine the following:

- Auditing the final account for time and cost benefits to the client;
- Identifying the areas in which time and cost benefits are located in the project;
- Analyse any potential further time and cost benefits in the project;

- Analyse local labour employment;
- Analyse local economic contribution; and
- Capturing the findings

6 References

Apis-cor. (2019). 3D Printed Homes | Apis Cor | United States. https://www.apis-cor.com/

Cobod. (n.d.). BOD2 - Modular 3D Construction Printer available now. Retrieved April 19, 2020, from https://cobod.com/bod2/

7 Annexures

Annexure A: Subsidy Housing Quantum

Annexure B: Bills of Quantities Breakdown

Annexure C: Priced Material List

Annexure D: LCC cash flow

Annexure E: LCC optional appraisal