3D-PRINTED HOUSES PILOT PROJECT

Research Report 1: Pre-production Phase

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1. INTRODUCTION

This Report is based on respondent perceptions of conventional and 3D-printed houses. Arranged in five sections, this Report is the first of a trilogy of surveys that have been planned as follows for the 3D-Printed Houses Pilot Project:

- Pre-production phase;
- Production phase; and,
- Post production phase:
    a. Social Acceptance; and,
    b. Technical Assessment.

1.1. Background

Unlike most other industries, the construction industry has not changed significantly in the twenty-first century: the processes and materials have remained essentially the same. And, bricks-and-mortar construction continues to monopolise the industry. As a result of this fixation, many valuable benefits that it might otherwise have enjoyed are lost to the industry.

A general reluctance by the construction industry to embrace technological advancement has meant that productivity is tedious, outdated and lacking in dynamism and creativity. There are various contributory factors. For example, there is insufficient collaboration between construction suppliers and contractors, inadequate knowledge transfer from one project to the next, and fear and anxiety by built environment professionals to explore innovative ideas and solutions. Yet, the construction industry is well-positioned to: refine its business-as-usual productivity and efficiency models; and, embrace technological advances such as Building Information Modeling (BIM), 3D-printing and augmented reality ((WEF), 2016).

3D-printing technology was developed in 1980 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 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, that commercialised the original rapid prototyping systems for CAD (computer aided design) software.

Also known as additive manufacturing, 3D-printing has since the 1980s infiltrated many industries including aerospace, art, medical and engineering.

The basic machine used in 3D-printing is a frame capable of moving in a two-dimensional plane and uses software to position the dispenser of materials.

The two main components of 3D-printing are:

- Method; and,
- Materials.

1.2. Research methodology

This pre-production survey used a quantitative methodology to gather and present the data. A structured questionnaire was used. A descriptive survey design was applied to collect data from respondents. The aim of this Report was to assess perceptions of respondents on conventional construction of a house, and also on 3D-printing of a house.

Due to the Covid-19 pandemic, the questionnaire could only be disseminated to respondents electronically. The completed questionnaires were uploaded on a spreadsheet. The data was uploaded twice by two different individuals. This was to ensure that there were no mistakes in the data capturing process. The data was then analysed.

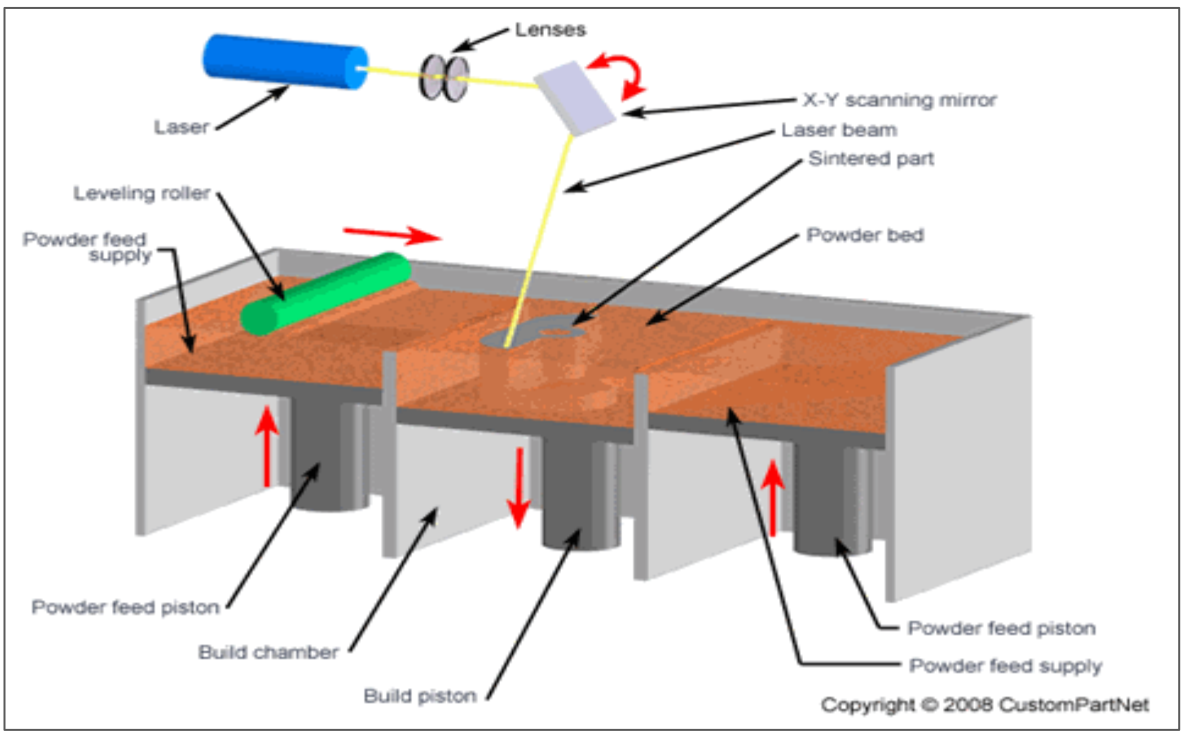
1.3. 3D-printing methods

The following section focuses on the methods used in 3D-printing.

1.3.1. Selective laser melting (SLM)

Selective laser melting (SLM) is a method where sintering takes place to form a 3D object. Sintering is the process of compacting and creating solid objects from material by using heat and pressure without melting the powder. The benefit of this method is that it does not require abundant additional sanding or alterations once an object is completed (Ngoa, et al., 2018).

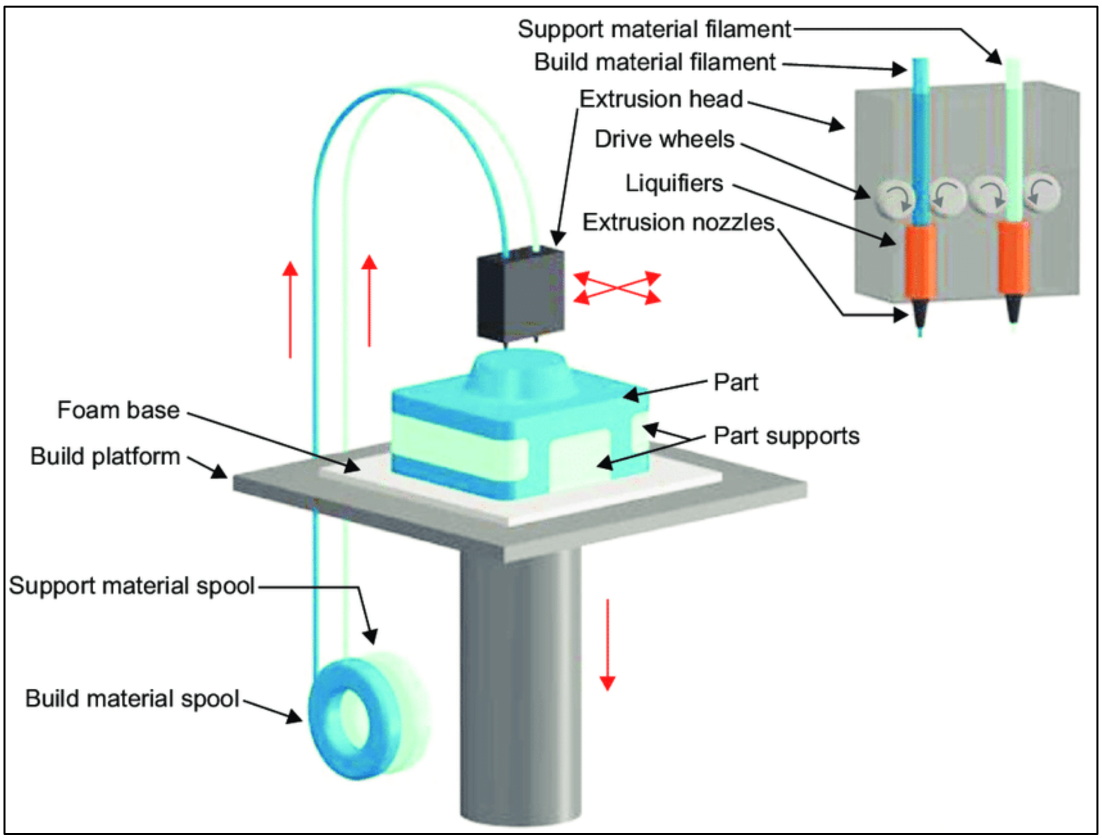
Figure 1.1: Selective Laser Smelting



1.3.2. Fused deposition modeling (FDM)

S. Scott Crump invented fused deposition modeling (FDM) technology in 1988 (Crump, 1996). Scott Crump is the founder, Chief Executive and Chairman of Stratasys Inc which is a 3D printing and additive manufacturing company incorporated in Israel. FDM transpires when material of a ductile nature is forced through a double-headed nozzle. The nozzle contains resistive heaters to keep the material at the required melting point and allows it to flow through the nozzle, which forms layers of material one on top of the other. After the material is pumped through the nozzle, it starts to cool and harden ready for the next layer to be placed on top.

Figure 1.2: Fused deposition modelling



1.3.3. Contour crafting (CC)

Contour crafting (CC) was invented by Professor Behrokh Khoshnevis at the University of Southern California. This is an additive fabrication technology. The method uses layer upon layer of material to create an object with smooth surface qualities. Some of the benefits of this method are an improved surface quality, broader choice of materials and a higher manufacturing speed (Sakin & Kiroglu, 2017).

Figure 1.3: Contour Crafting 3D-printer

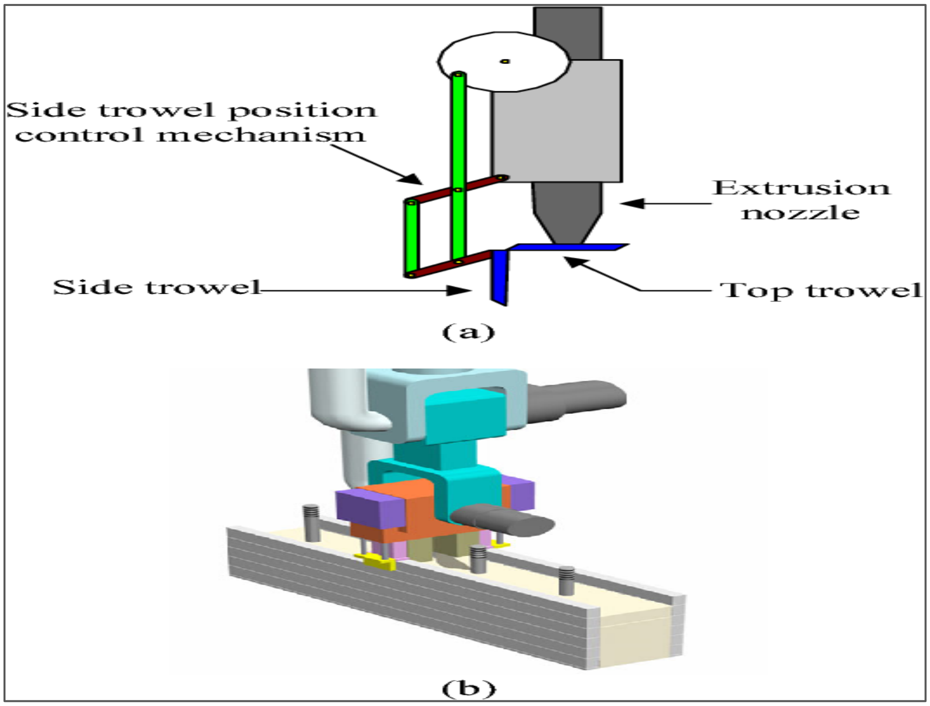


Figure 1.4: Individual layers of cement on a structure created by Constructions-3D

1.4. 3-D printing materials

1.4.1. Selective laser melting (SLM)

The materials used most frequently for SLM are metallic based powders which are fused together. The latest advances of fibre optics and high power lasers have permitted SLM to process various metallic materials like aluminum, copper and tungsten.

1.4.2. Fused deposition modeling (FDM)

Materials used most often in FDM are filaments or rolls of thermoplastic material like acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA). ABS is available in a wide range of colours. PLA is made from biodegradable material that contain cornstarch or sugar cane. Fused deposition modeling has become the most popular type of 3D-printing used globally (Ngoa, et al., 2018).

1.4.3. Contour crafting (CC)

Contour crafting uses materials which are quick setting, for example, concrete and sand.

1.5. General industrial use of 3D-printing methodology

The 3D-printing methods and materials discussed in the previous section have been used in various industries primarily for the development of prototypes.

The adaption of 3D-printing methodology in the medical and dental prototyping industry to create unique working models for each patient individually is discussed in Jeffrey et al (Jeffrey W.Stansburya & Idacavagec, 2016). 3D-printing methodology is also used to print bone and cartilage as well as replacement tissue and organs to assist with cancer research (Wang1, et al., 2018).

In the aerospace industry, 3D-printing is applied where lightweight parts are essential and require complex geometric shapes. Where engine components are easily damaged and must be replaced in a short time span, 3D-printing has been used as the process to reproduce these parts is less time consuming (Ngoa, et al., 2018).

Artists and designers use 3D-printing to visualise the concepts of their work from a digital image to a physical prototype before the product is ready for production. Artists are also using 3D-printing to create once-off or limited edition art. At the Massachusetts Institute of Technology, 3D-printing is utilised for the improved perception of ancient artifacts. This process includes the designing of artifacts, sculptures, and jewellery (Franco, et al., 2015).

It is clear that 3D-printing has assisted in various industries to increase productivity and improve efficiency.

1.6. House production using 3D-printing methodology

The previous section showed that various industries have successfully used 3D-printing. The construction industry is also investigating new ways to improve production and efficiency.

The Amsterdam Canal House Project in the Netherlands commenced using 3D-printing in 2014. The printing of the house is still in progress and will consist of 13 rooms which require various 3D printed elements (HOUSE, 2016). The walls and floors are printed using 3D technology and then just click into place similar to giant Lego blocks.

Shanghai WinSun Decoration Design Engineering Company in China 3D-printed ten houses in 24 hours. The pieces of the houses were printed and then transported from its industrial park to the Shanghai's Qingpu district site (Kira, 2015). The same company has completed a six-storey apartment building covering approximately 1100 square metres with 3D-printing technology. The materials used for this apartment building included waste such as fibreglass, concrete, sand and a special hardening agent. This technology is relatively unknown in the building industry and has not been applied to any building construction in South Africa as yet.

A low cost housing solution in Cape Town involves an earth bag building system whereby walls are constructed out of sandbags which are then covered in earthen plaster as a finish to the walls (Brendan Grady, 2019). These include methods to lower the cost of construction and materials as well as a reduction in project completion time.

Concrete is one of the main materials used in the construction industry globally. The raw materials required are relatively inexpensive and readily available in most countries. Although concrete is one of the best materials to use in construction, it has some disadvantages, which can ultimately have a cost implication. Some of the disadvantages associated with concrete are that it is a quasi-brittle material; and has low tensile strength, toughness and specific strength. Concrete also requires formwork and a long curing time. All these require strict quality controls. The construction industry is investigating methods to negate some of the disadvantages of traditional building material and methods. The World Economic Forum started a multi-year effort to help the construction and engineering industry with this ((WEF), 2016).

1.7. Advantages and disadvantages of 3D-printed houses

In this section, we list the advantages and disadvantages of using 3D-printing methodology to produce houses in South Africa.

1.7.1. Advantages

The advantages of producing houses using 3D-printing are as follows:

- creating components with unlimited architectural flexibility and higher precision (Hager, et al., 292 – 299)
- reducing health and safety risks
- Increasing production efficiency

1.7.2. Disadvantages

The disadvantages of producing houses using 3D-printing are as follows:

- the equipment may be large, resulting in high transport and placement costs
- can be a costly process in terms of the amortisation of expensive equipment
- material with unique properties focused on construction may be expensive
- the technology is not proven in South Africa

The advantages and disadvantages will need further investigation before any definitive conclusion may be drawn on whether or not 3D-printing increases production efficiency and reduces the time it takes to complete a house.

2. AIM OF THE SURVEY

This survey aims to get an indicative idea of stakeholders' views on 3D-printed houses.

3. DATA ANALYSIS AND INTERPRETATION

The survey used a structured questionnaire to elicit responses from housing stakeholders. This structured questionnaire is attached to this Report as Appendix A.

The quantitative information derived from administering the survey questionnaire was collated and analysed. Consisting of five sections, the questionnaire uses an exploratory research design method. An exploratory research design method focuses on investigating a problem, and in doing so discovers a better understanding of the problem. This survey explores respondents' views on conventional building of houses, their knowledge and experience of 3D-printing in general, and their views of 3D-printing of houses specifically.

Table 3.1: Outline of the survey design

Conventional construction methods and materials	This section is mainly centred on "building" houses using bricks-and-mortar
3D-printing (general)	This section probes respondents' knowledge of 3D-printing methodology in general
3D-printing (house production)	This section probes respondents' knowledge of 3D printing in relation to the production of houses

3.1. Sampling

3.1.1. Sampling criteria

A sample is a small group of respondents that has been chosen from a larger group. But the sample must still represent the larger group (Polansky, 1995). Random sampling was used to distribute the questionnaire to respondents.

Respondents were not required to disclose their names. As a result, 2 of the 27 respondents chose to remain anonymous.

3.1.2. Criteria for choosing respondents

Those targeted by this survey included built environment professionals and artisans, contractors, developers, homeowners, home-seekers, government officials involved in the sector and bank employees involved in housing finance.

The restrictions related to the Covid-19 pandemic made face-to-face interviews impossible. The questionnaire had to be emailed to respondents. And this proved to be less than ideal. Indeed, Kwak showed in his 2002 study that the response rate to emailed surveys is almost always lower than hand-delivered surveys.

3.1.3. Sample size and response rate

The questionnaire was disseminated to 49 built environment stakeholders. Of these, 27 responded by completing the questionnaire. This equated to a response rate of 55.10 percent. It was also deemed an adequate sample size and response rate to proceed with.

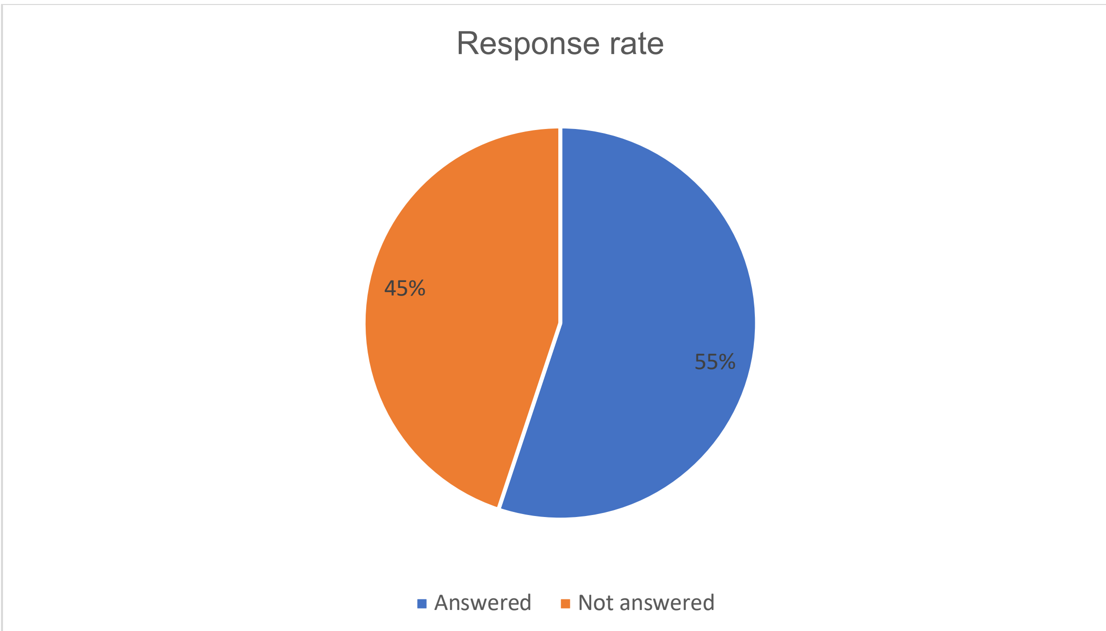


Figure 3.1: Survey response rate

The questionnaire did not require respondents to add their name. However, it was a prerequisite for respondents to include their professional status. Of the 27 respondents, 32 percent was from the Civil Engineering discipline. Eighteen percent of respondents were from the Electrical Engineering discipline and 8 percent were from the Mechanical Engineering discipline. Twenty-two percent of respondents worked in the Project Management sector, and the remaining 20 percent was evenly distributed among the marketing; design; education; metal; and, construction and mining sectors. Every effort was made to distribute the questionnaire especially to built environment professionals as well as home seekers and financers. But, there was a nil return from home seekers and financers, and any further enquiries could not be pursued because of restrictions relating to the Covid-19 pandemic. The demographic information of the 27 respondents shows that 67 percent was male and 33 percent, female.

3.2. Data analysis

3.2.1. Conventional house building methods and materials

Section A of the survey explored views on building methods that use bricks and blocks. These questions focused on what methods the respondents were familiar with and the materials used to build a house.

3.2.1.1. Methods to produce houses

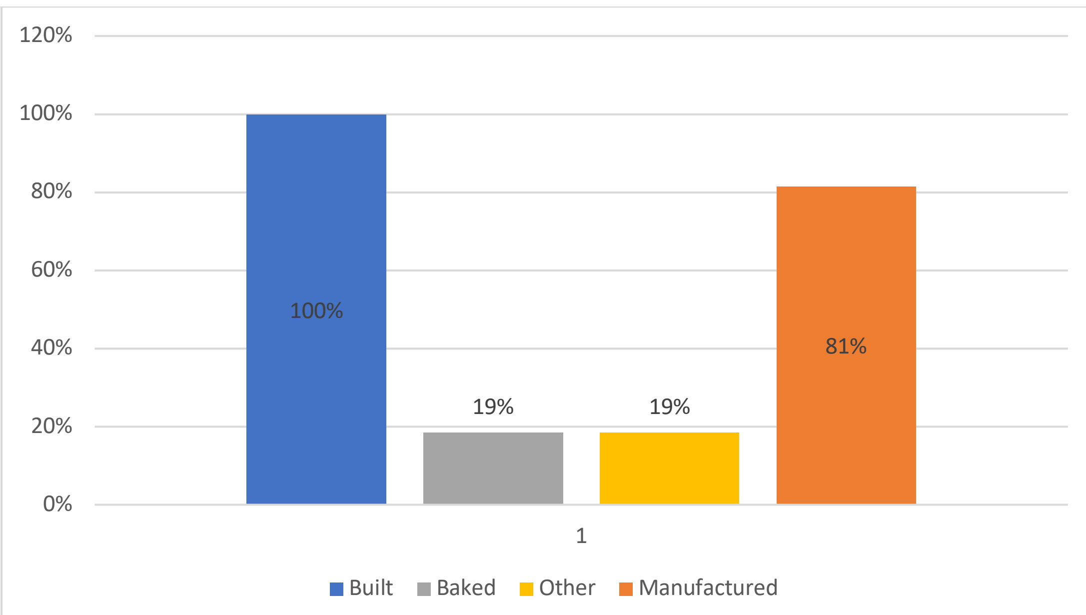


Figure 3.2: Methods to produce houses.

All of the respondents (100 percent) stated that the use of bricks and mortar ensured decent houses. Alternatively, manufacturing a house as second choice was selected by 81 percent of respondents. Fifteen percent of respondents chose only one answer for this question; the other 85 percent chose more than one option. Some of the other methods mentioned were subterranean, recycled containers and wood mouldings. The respondents that stated "houses can be baked" were contacted to find out why they chose this answer because houses cannot be baked. All five of them answered that they meant sections of the houses could be baked, and then assembled on site.

One can conclude that although 100 percent of respondents were confident about building a house with conventional materials, 19 percent of them still indicated that they would consider using alternative methods and materials.

3.2.1.2. Walls

Respondents were asked what could be put together to make walls. The figure below shows their responses.

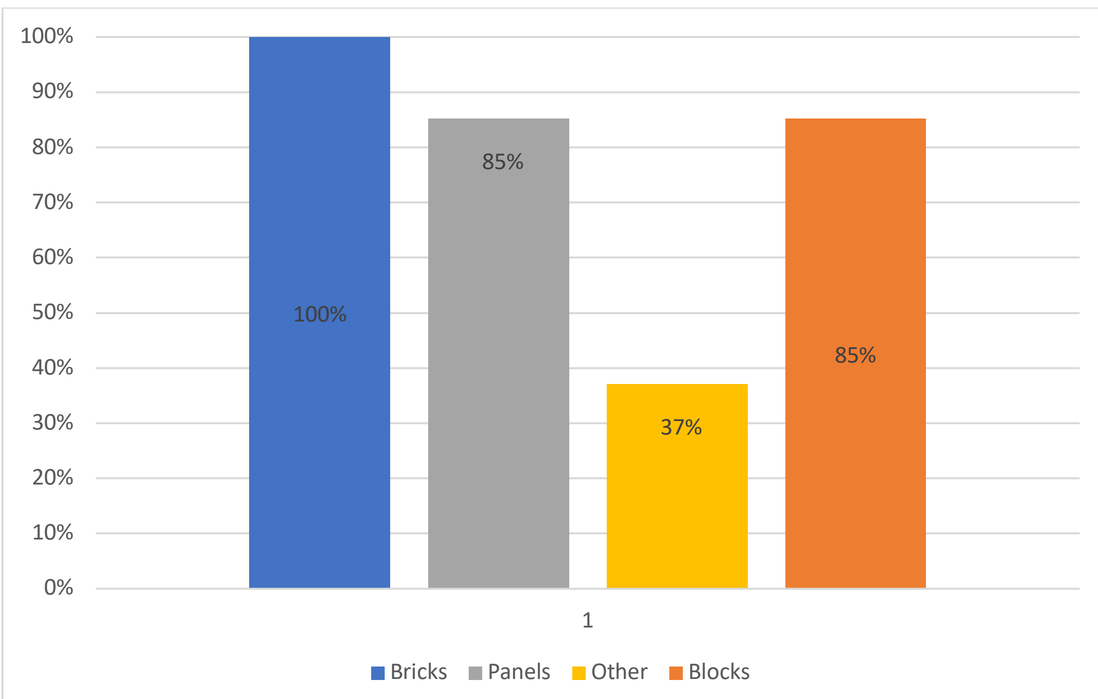


Figure 3.3: Walls

All of the respondents stated that bricks could be used to make proper house walls. Eighty five percent indicated that panels and blocks could also be used for the same purpose. Under "other", some respondents cited concrete slabs, stone cladding, steel or iron walls, timber, corrugated metal, bamboo and stone. Some stated that natural materials such as fibres and mud could also be used to make proper house walls.

3.2.1.3. Materials for bricks, blocks and panels

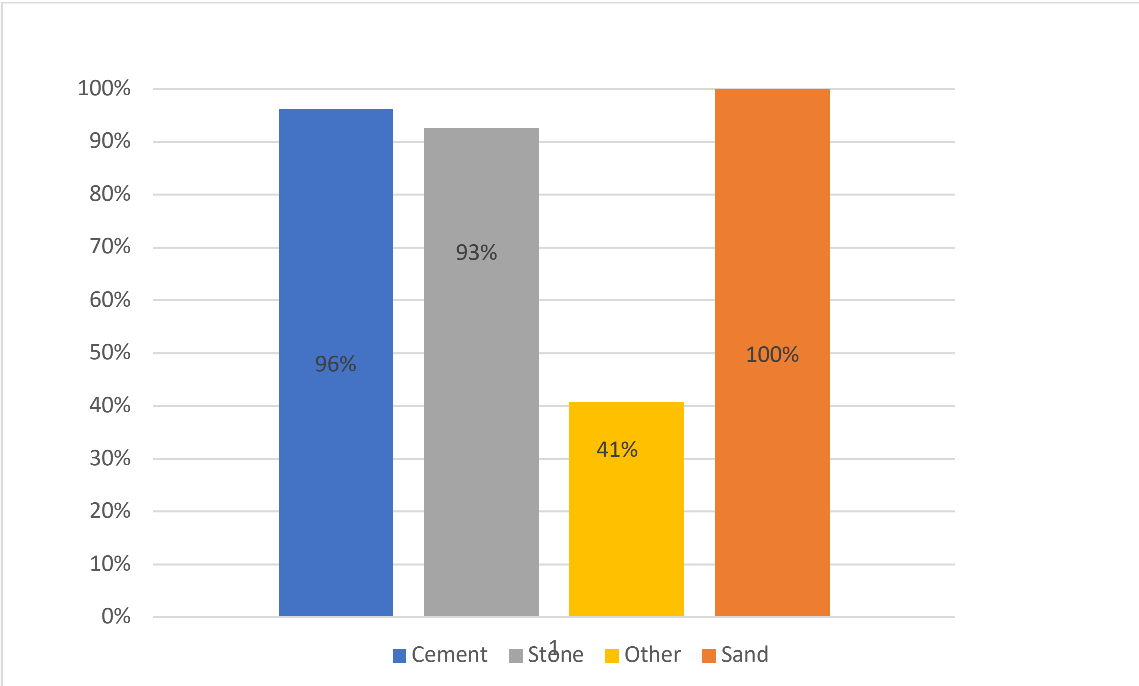


Figure 3.4: Materials for bricks, blocks and panels

Of the 27 respondents, only 11 percent did not choose all three options of cement, sand and stone as materials used to make bricks, blocks and panels. As illustrated in figure 5, sand had a response rate of 100 percent, while cement and stone had response rates of 96 percent and 93 percent respectively. This was for materials that can be used in the production of bricks, blocks and panels.

As shown in figure 5, some of the other materials mentioned were clay and ash. A significant proportion of the world's population lives in and or works in a building that is prepared with clay as a crucial part of its load-bearing structure. Some products derived from clay are paving bricks, terra cotta tiles, drain pipes and building bricks.

In South Africa, clay bricks predominate for wall construction. Fly ash is a big contributor in green engineering. It is used as a component of concrete to produce a durable and sustainable structure.

Although clay, cement, stone and sand have been specified as the preferred material for building a house, 41 percent of respondents indicated that they would consider ‘other’ material as the base material for making bricks, blocks or panels.

3.2.1.4. Pre-eminence of bricks-and-mortar houses

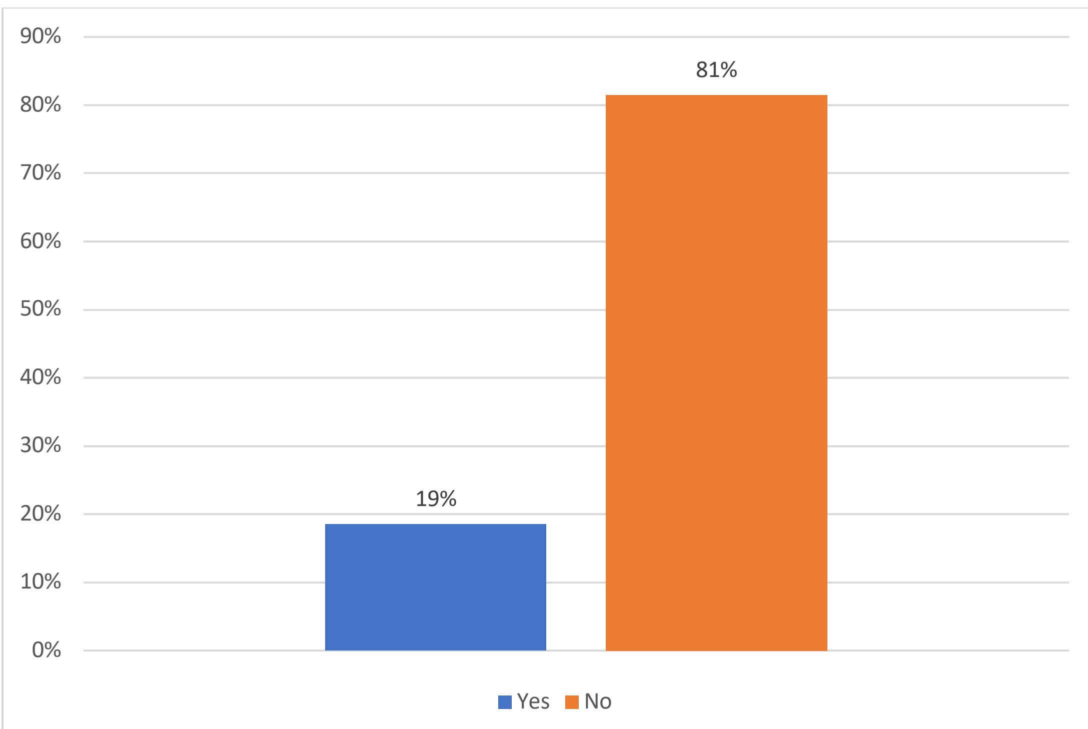


Figure 3.5: Pre-eminence of bricks-and-mortar houses

The majority of respondents (81 percent) stated that houses built of brick and blocks should not be the only houses allowed in South Africa. Building houses exclusively from bricks and blocks have a significant impact on sustainable development, cost of building as well as the shortage of resources and the high cost of building materials in the construction industry.

In South Africa, there is a significant shortage of housing which can be seen as a palpable asset to the less privileged (Burgoyne, 2008). The construction industry is known for being a major consumer of non-renewable resources and finding ways to rectify this through sustainable development can have a positive impact.

The high cost of building material contributes to the South African housing crisis. Exploring ways to reduce material cost and re-using material would impact the methods which the building industry employs to constructs houses. Additionally, respondents aver that poor people cannot afford houses built from bricks and blocks and should be able to use whatever material they can find.

Wood, corrugated-iron sheets and clay were among the other materials respondents nominated.

Eighty-one percent agreed that houses could be built with material other than bricks or blocks. This indicates that alternative materials and methods are acceptable for the building of houses in South Africa.

3.2.1.5. Respondents' views on the shortage of houses in South Africa and how this can be resolved

This question generated varying responses. These included:

- "to stop corruption and fraud through funding for low cost housing going missing"
- "Put an end to moving the goal posts about 'affordable' housing"
- "Endeavour to employ alternative means of building houses, considering cheaper building methods and materials as well as building low cost multi-level houses"

The results of Section A of the survey indicate that the respondents are in general agreement that alternative materials and methods could be considered.

3.2.2. Materials used in conventional building of houses

Section B of the questionnaire focused on the type of materials used in the building construction industry.

3.2.2.1. Additional materials used to produces houses

The majority of respondents (96 percent) answered that they have seen other materials being used in the production of houses. They mentioned fibre panels, preformed walling, mud and straw, in-situ cast concrete as well as concrete and glass bottles (for aesthetic reasons), recycled materials and modular panels. Modular panels are interlocking panels that are lightweight, fire resistant and insulated to create affordable prefabricated housing and is being made by various companies in South Africa already.

Figure 3.6: Bottle Houses at Prince Edward Island

Figure 3.7: The Bottle Chapel at Airlie Gardens, North Carolina.

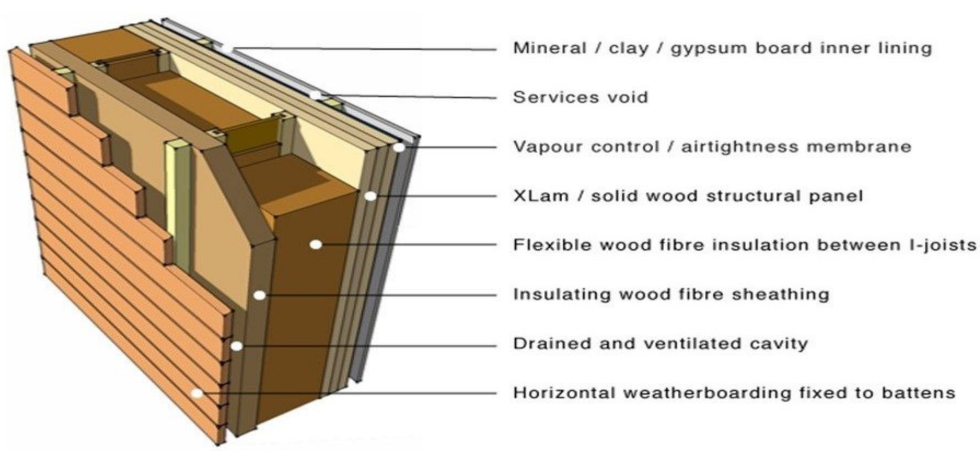


Photo source: GreenSpec UK

Figure 3.8: Wood Fibre wall

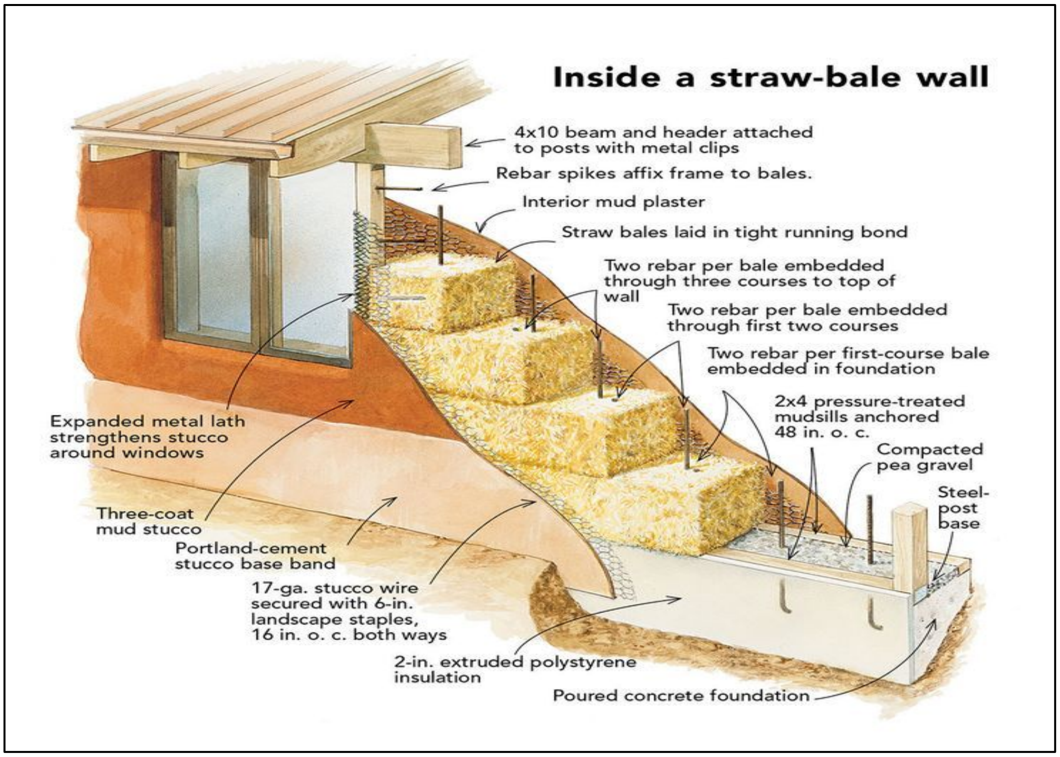


Figure 3.9: Mud and straw wall

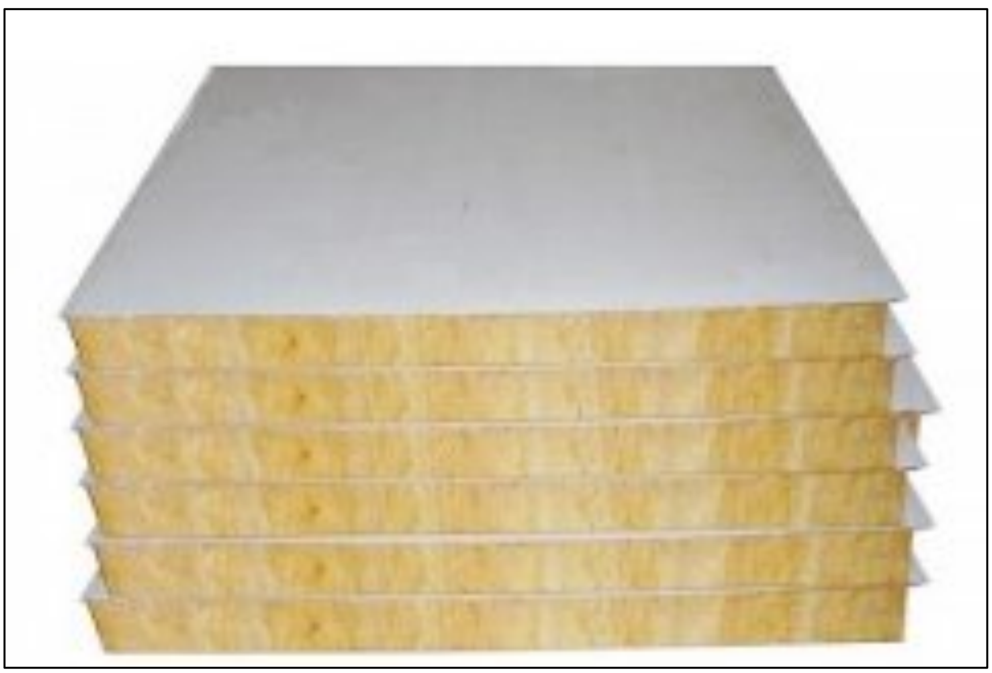


Figure 3.10: Steel sheeting and rock wool inner core wall

3.2.2.2. Materials used in house production

Eighty five percent of respondents agreed that the materials they have listed were solid enough to make the walls of a house. According to SANS 10400 – A – 2010 A13 Building Materials and Tests "Material used in the erection of a building shall be suitable for the purpose for which it is to be used." This indicates that any house produced through 3D printing will need to go through relevant non-destructive testing to ensure that the material being used is appropriate for the purpose it is intended for (SABS, 2010). The South African Bureau of Standards approves new methods and materials used for building. This is to ensure the quality of design and adherence to safety regulations (Douglas Aghimien, 2019).

According to the "Policy guidelines on the use of innovative technologies within the Kwazulu-Natal Department of Human Settlements", any house being erected needs to comply with the following critical quality aspects: structural strength and stability; thermal and energy performance and/or efficiency; water penetration; behavior in fire; durability; condensation; quality management system; cost; and, design (guidelines, n.d.).

According to these Guidelines an innovative housing system includes: the use of new materials; new ways or methods of applying traditional materials; improvements in designs to enhance functionality of a house; system designs (designing for energy efficient house); and, performance-based design fit for purpose.

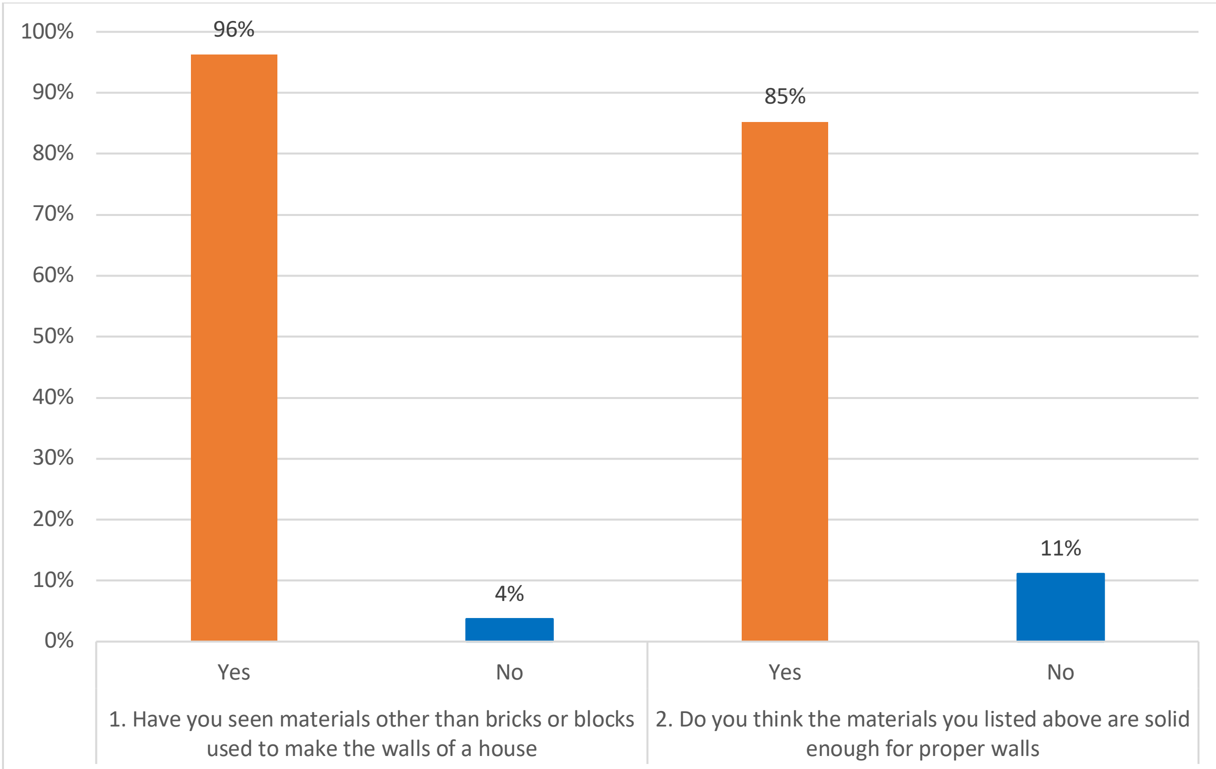


Figure 3.11: Materials used in house production.

The respondents' feedback for Section B indicate that the types of materials used in the building construction industry are regulated. However, 96 percent respondents indicated that they had witnessed materials other than bricks or blocks used in the construction of houses. They mentioned fibre panels, preformed walling, mud and straw, in-situ cast concrete as well as concrete and glass bottles. Eighty-five percent believed that these were solid enough for use in wall construction. This supports the theory that respondents are in agreement that alternatives materials and methods should be considered.

3.2.3. General knowledge of 3D-printing

Section C of the questionnaire required information on 3D-printing and the respondents' knowledge of any kind of 3D printing.

3.2.3.1. General knowledge of 3D-printing

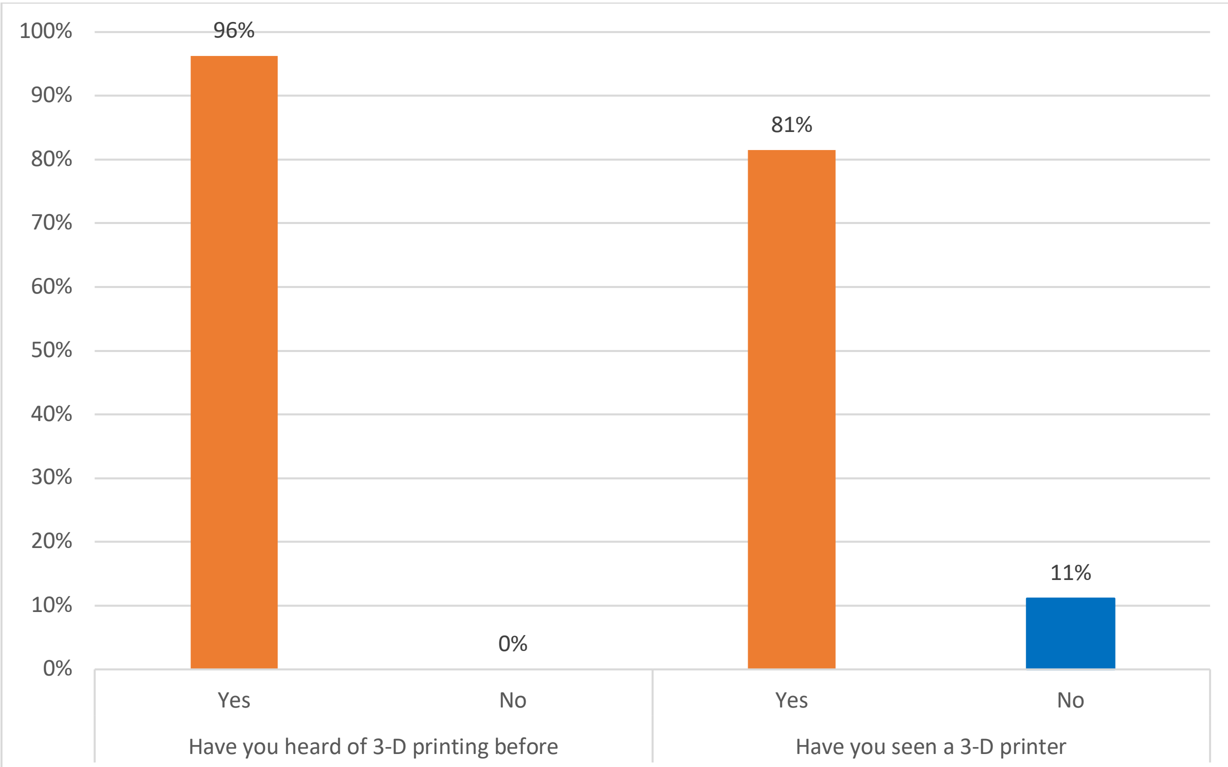


Figure 3.12: General knowledge of 3D-printing

An overwhelming majority of the respondents (96%) had heard of 3D printing and 81 percent had seen a 3D-printer being used. The 8 percent that had never seen a 3D-printer being used but had heard of 3D printing, was asked why they had never seen a 3D- printer being used. Most respondents answered that they did not require anything to be 3D-printed and, therefore, had no reason to see a 3D-printer being used. Some of the respondents also stated that although they were too busy to watch videos on 3D-printing they did know what 3D printing was. Two of the 27 respondents did not answer the question.

3.2.3.2. General experience of 3D-printing

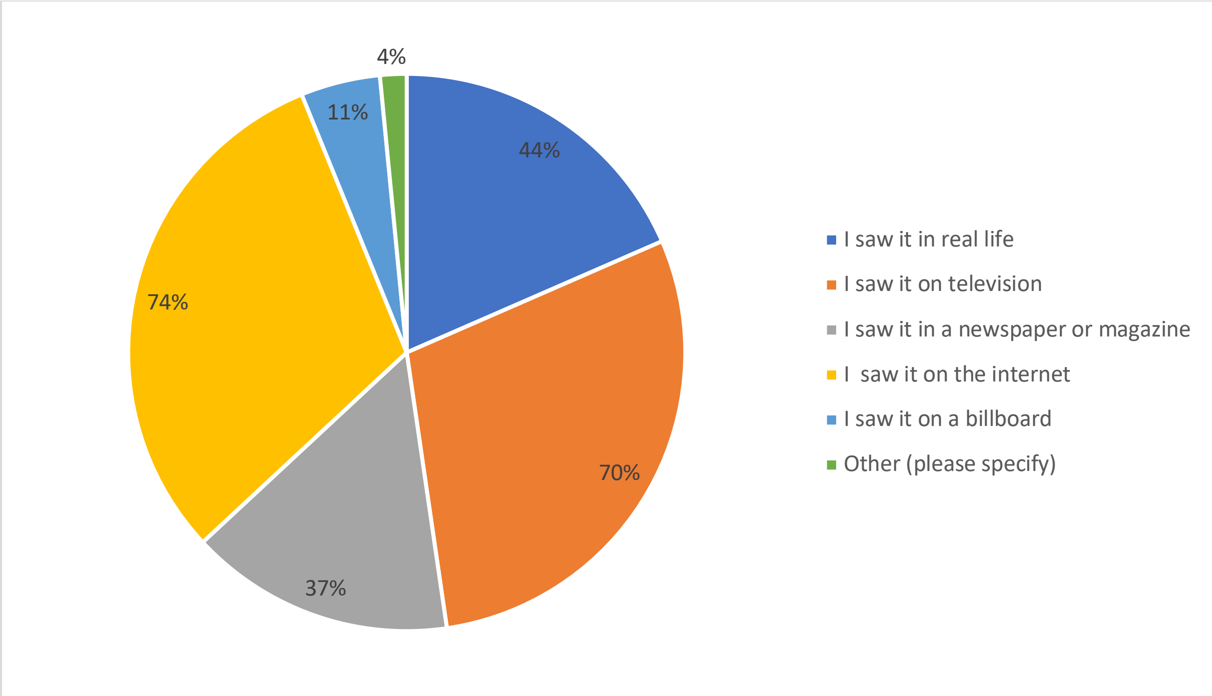


Figure 3.13: General experience of 3D-printing

Information regarding where respondents had seen a 3D-printer is shown in figure 14. It shows that 74 percent had seen 3D-printing on the internet and 70 percent saw it on television, in either a movie or series. Three of the 27 respondents became aware of 3D-printing when watching a three part series on television entitled “3D-print the future” which aired in 2017.

The respondent that selected ‘other’ owned his own 3D-printer. He used Polylactic (PLA) to print. Commonly used by hobbyists, this material is an environmentally friendly filament, which consists of cornstarch and sugar cane. It is known for its strong consistency qualities as well as the ability to resist UV light. Acrylonitrile butadiene styrene (ABS plastic) is another material commonly used in 3D-printing (Kuneinen, n.d.).

The remaining 96 percent of respondents indicated second-hand knowledge of 3D-printing in that they had all only seen and heard of 3D-printing via the electronic and printed media. This is an indication that all besides one respondent had first-hand knowledge or experience of the practical operation of the 3D-printer.

3.2.4. General knowledge of 3D printing of houses

Section D of the questionnaire was based on the respondents' knowledge of 3D-printing of houses.

3.2.4.1. Knowledge and experience of 3D-printing of houses

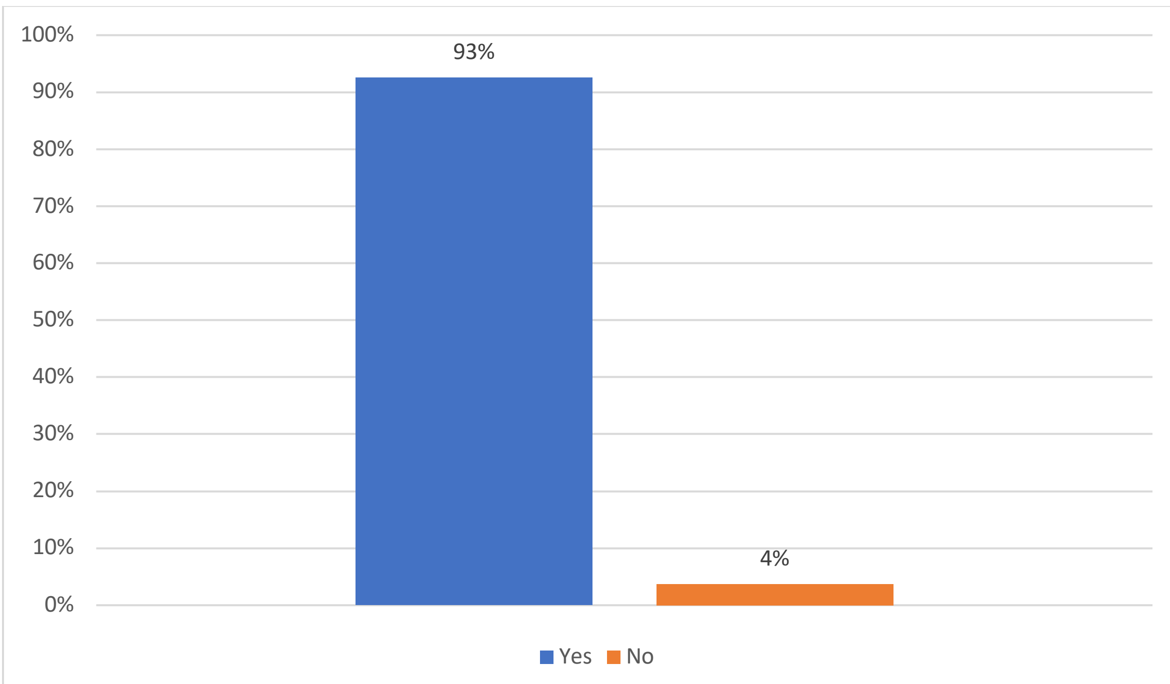


Figure 3.14: Knowledge and experience of 3D-printing of houses

The majority of respondents (93 percent) answered that they thought it was possible to 3D-print a house.

This is an indication that the respondents generally believed that it was possible to 3D-print a house or, at least, segments of a house.

3.2.4.2. 3D-printing house parts

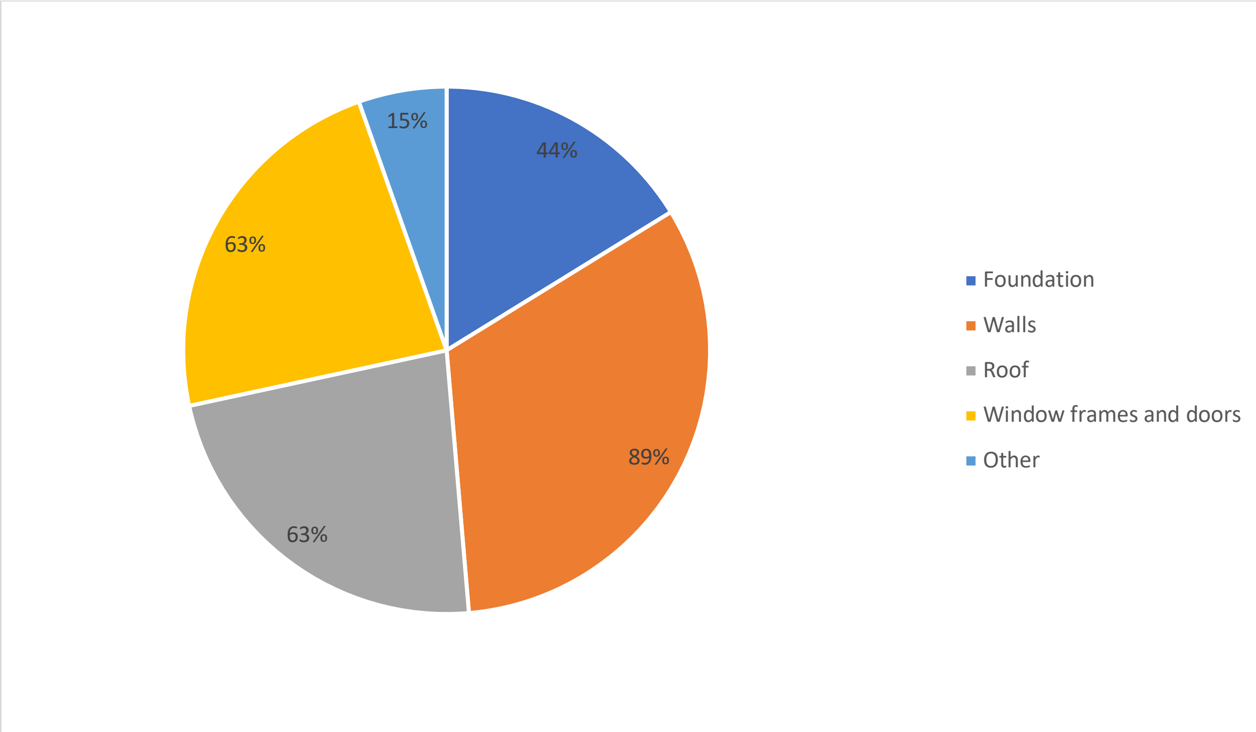


Figure 3.15: 3D-printing house parts

This question had varied responses. Eighty nine percent of respondents believed that walls could be completed through 3D-printing, and 63 percent said that window-frames, doors and the roof could be completed through 3D-printing.

The remaining 37 percent that did not think windows-frames, doors and the roof could be 3D-printed believed that only the openings for these could be done while the walls were being 3D-printed. The respondents believed that the actual doors and windows would have to be manufactured and then slotted into the wall openings either during the 3D-printing process or after the walls were printed. They also stated that the roof would have to be manufactured after the 3D-printing process was completed.

3.2.4.3. **3D-printing house shapes**

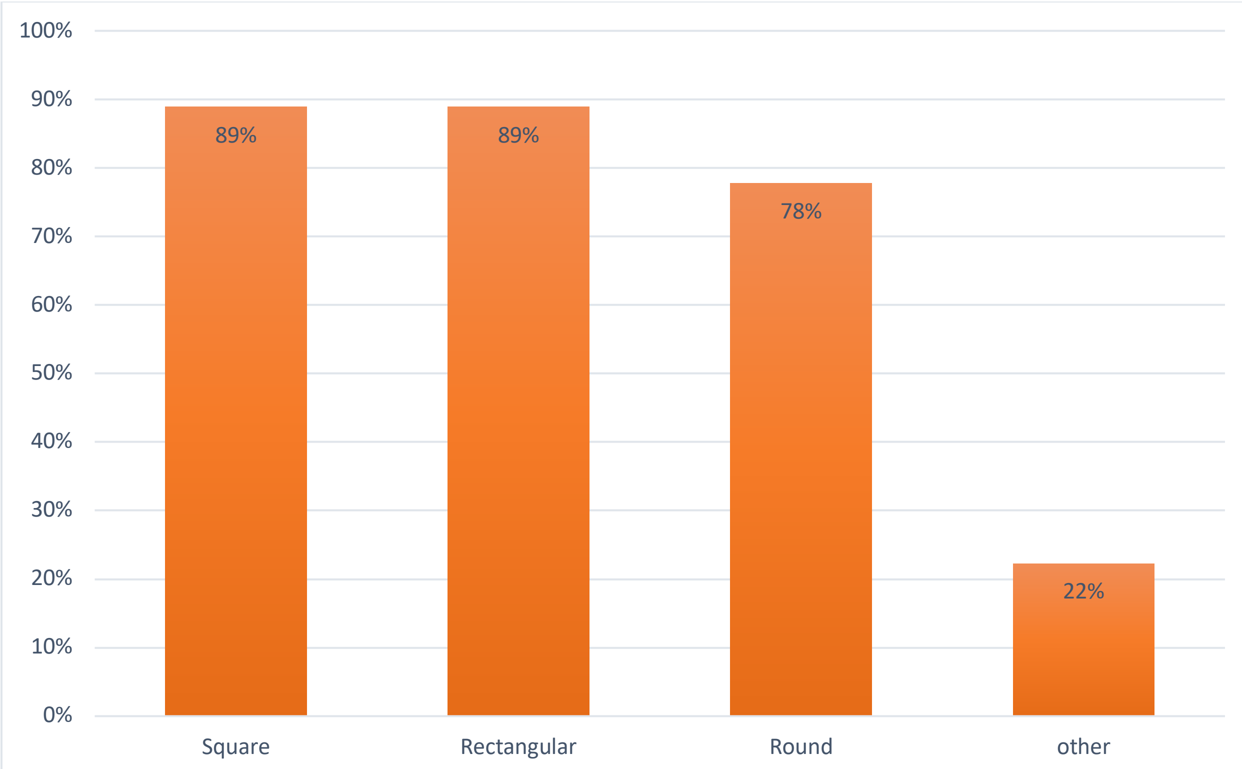


Figure 3.16: 3D-printing house shapes

A large number of respondents (89 percent) thought that a house could be 3D-printed in a square and rectangular shape, and 78 percent of respondents thought a house could be 3D-printed in a circular shape. The 22 percent that answered 'other' for the shape that could be 3D-printed stated that any realistic and uncomplicated shape could be 3D-printed.

Respondents viewed 3D-printing as providing varied products. Under Section A they had believed it possible to 3D-print using a multiplicity of methods and materials. And, in this Section they are generally of the view that virtually any shape of house could be 3D-printed.

3.2.4.4. 3D-printing house sizes

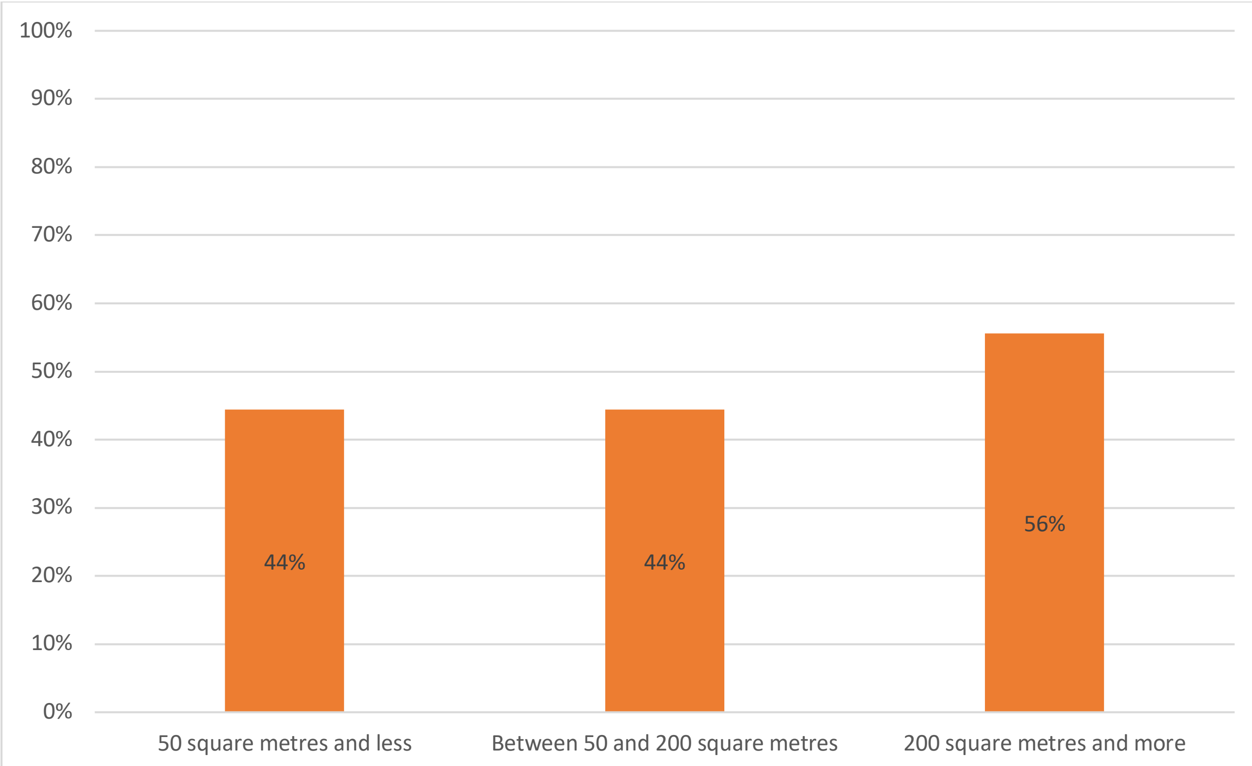


Figure 3.17: 3D-printing house sizes

Fifty six percent of respondents stating that the biggest sized house that could be 3D-printed was 200 square metres or more. Less than half of them (44 percent) stated that the biggest sized house that could be 3D-printed was either “50 square metres or less” or “between 50 and 200 square metres”.

3.2.4.5. 3D-printing house types

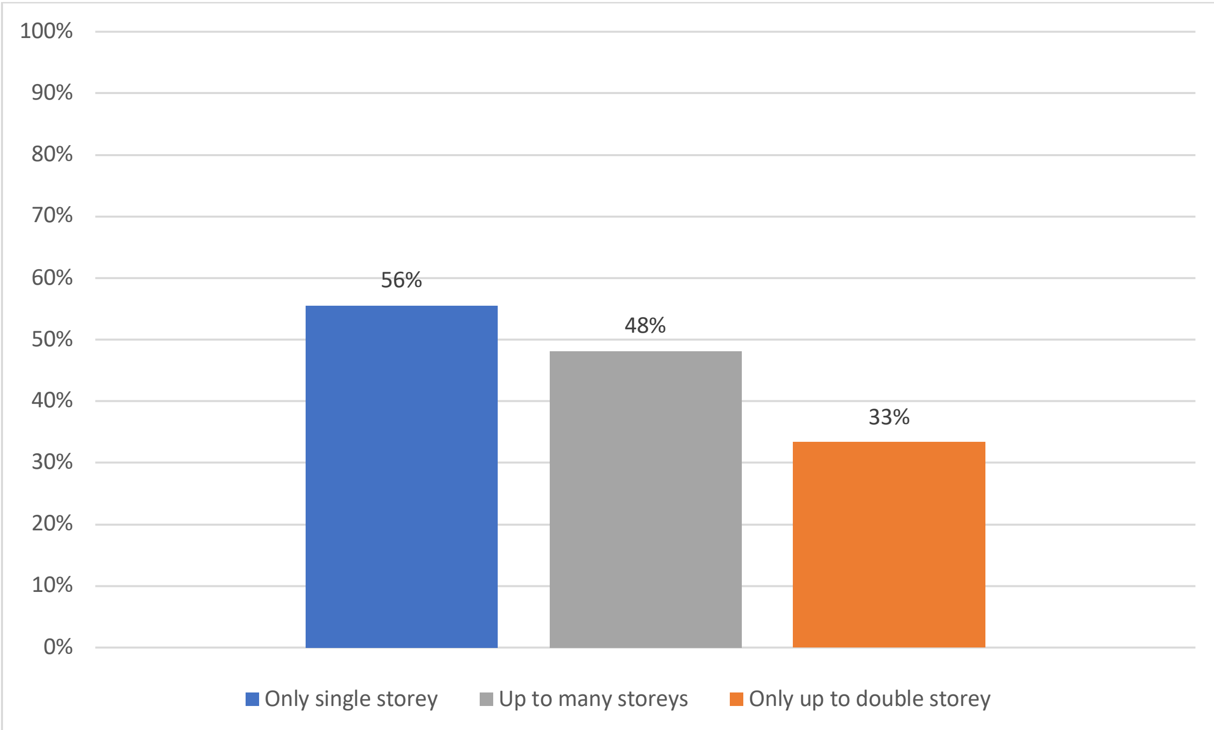


Figure 3.18: 3D-printing house types

Forty eight percent of respondents thought that a multi-storeyed house could be 3D-printed.

The rest of the data could not be interpreted intelligently as despite directions not to do so, most of the respondents had ticked more than one box.

3.2.4.6. Benefit of Simplicity: 3D-Printed House vs. Conventionally Built House

Seventy five percent of respondents thought that it would be easier to produce a house through 3D-printing because it is an automated process. They reasoned that the work completed by a machine was easier than work completed by human beings. Some of the respondents thought that there would be fewer mistakes if a house was 3D-printed using a machine or computer.

3.2.4.7. Benefit of Speed: 3D-Printed House vs. Conventionally Built House

This question had the second highest positive response rate compared to the other questions related to easier, cheaper, better and safer at 85 percent where respondents thought that 3D printing of houses would go faster than conventionally built houses.

The respondents asked to clarify this statement said that with the knowledge they have of 3D printing, 3D printing would be faster than conventional built houses because of the human factor involved.

3.2.4.8. Benefit of Cost: 3D-Printed House vs. Conventionally Built House

Fifty six percent of the respondents thought that 3D-printed houses would be cheaper than conventionally built houses. When asked why they thought that this was the case, they indicated that although 3D-printing set-up costs could be more production would still be faster. Also, the need for less labour on site could add to reducing cost.

A University of Johannesburg Quantity Surveyor did a cost analysis, and the typical costs associated with conventional building and 3D printing using a gantry system is presented in the table below.

Table 3.2: Cost analysis of conventional construction versus 3D printing

Cost of construction	Conventional	Gantry	% Savings
Foundations	R30,129.58	R30,129.58	0.00%
Wall Plates/ Block-work	R23,414.03	R16,000.00	31.66%
Roofing	R15,951.01	R15,951.01	0.00%
Finishes	R21,934.64	R21,934.64	0.00%
Electrical	R4,666.26	R4,666.26	0.00%
VIP Toilet	R7,938.23	R7,938.23	0.00%
Tank stand & Rain water goods	R4,973.17	R4,973.17	0.00%
Sub-Total	**R109,006.92**	**R101,592.89**	**6.80%**

3.2.4.9. Benefit of Physical Improvement: 3D-Printed House vs. Conventionally Built House

Fifty six percent of respondents thought that 3D-printed houses would be better than conventionally built houses. These respondents stated that there would be less mistakes made with 3D-printing. Some respondents also stated that the material used to 3D-print the house would be consistent throughout the production process. The house could be designed according to the homeowner's preferences (any shape and size) and be implemented in a short time span. This would then result in each house being unique.

The 41 percent of respondents who believed that 3D-printed houses would not be better stated that the technology was too new and they, therefore, were not certain about a 3D-printed house. These respondents also stated that they would need some form of assurance that 3D-printed houses would be as structurally sound and secure as conventionally built houses.

3.2.4.10. Benefit of safety: 3D Printed House vs. Conventionally Built House

Of the five questions related to 3D printing being easier, faster, better and cheaper than conventionally built houses, the question on whether or not respondents thought it would be safe to live in a 3D-printed house had the highest positive response rate (89 percent).

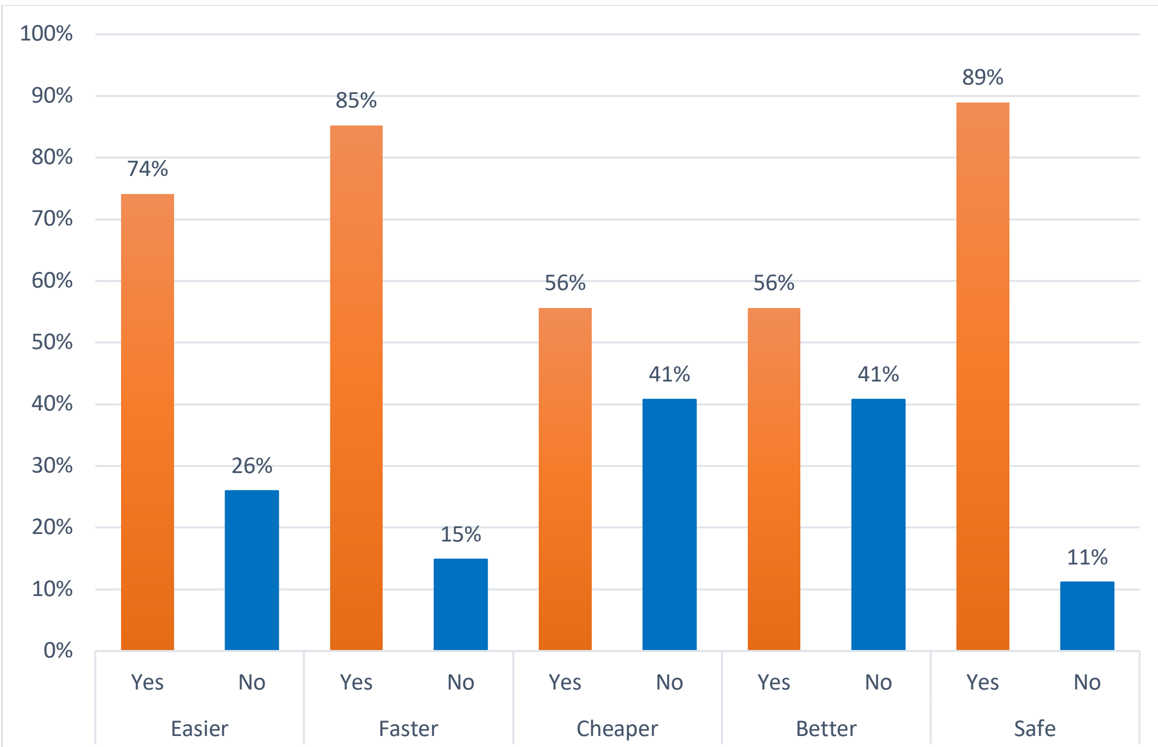


Figure 3.19: 3D-printed houses versus conventionally produced houses

In summary, there is consensus among the respondents that a 3D-printed house was better than conventionally built houses with regard to: ease; speed of building; cost; environmental benefits; and, safety.

3.2.5. Potential impact of 3D-printing of houses

Section E of the questionnaire considered other facets of 3D-printing such as which occupational groups would be affected.

3.2.5.1. Professionals and artisans affected by 3D-printing of houses

According to figure 18, 85 percent of respondents assumed bricklayers would be adversely affected by 3D-printing of houses. Respondents stated that a bricklayer would become obsolete because bricks would no longer be used. Some respondents suggested that bricklayers could be re-skilled in other aspects of the construction process.

A majority of respondents (63 percent) indicated that plasterers would also be rendered superfluous with houses being 3D-printed. They stated that depending on the finishes of a 3D-printed house, the plasterer might still be required to give the house a smoother finish.

Fifty six percent of respondents indicated that structural engineers and architects would be negatively affected by 3D-printing of houses. They indicated that while architects and structural engineers would still be required at the commencement of a project, they would not be required once the designs have been approved and the structural analyses completed.

About a third of the respondents (30 percent) thought that carpenters, roof installers, electricians and plumbers would be affected by 3D-printing of houses. The roof installer would be affected because it is also possible to 3D-print the roof. And, although the carpenter would not need to erect wooden structures, he would still likely be required to install doors and window frames as well as shelves and cabinets.

Many respondents believed that electricians and plumbers would still need to install and sign off on electrical cabling and pipes. But they also acknowledged that conduit and pipe openings could also be provided for by the 3D-printing process.

Less than half of the respondents (44 percent) stated that developers and contractors would be affected by 3D-printing of houses because they are accustomed to working with bricks-and-mortar through a conventional process. And, 3D-printing implies a "business unusual" situation which necessitates them, at best, developing new skills and knowledge that relate to 3D-printing.

Homebuyers would be affected because ultimately, they would need to feel confident that their 3D-printed house is at least the same standard as a conventionally built house.

Some of the respondents were concerned about job losses that would likely occur as 3D-printing of houses takes root. But re-skilling remains a viable option. Every industrial revolution has changed the way business takes place, and the standard of living for the majority of people around the globe has improved greatly as a result (Xu, et al., 2018). As part of the fourth industrial revolution inventory, 3D-printing will have a significant impact on people. This potential impact must be embraced as an opportunity to be seized on. Better understanding of it will ensure that jobs are preserved or created.

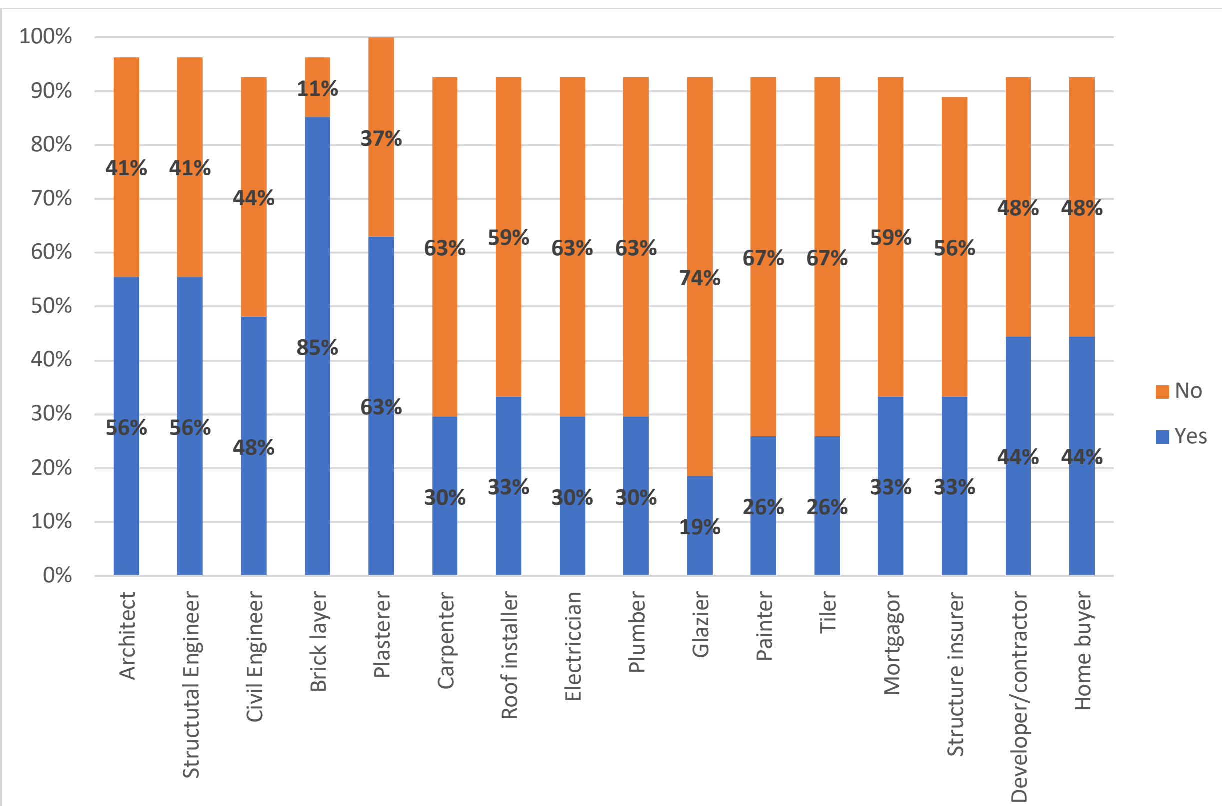


Figure 3.20: Professionals and artisans affected by 3D-printing houses.

In summary, respondents were of the view that job losses will occur, with bricklayers potentially the worst affected. However, technicians such as electricians, glaziers, plumbers and carpenter will be less affected because of the ongoing need for their services, most of which cannot be replaced by a 3D-printer.

Besides bricklayers, respondents also felt that architects, structural engineers and civil engineers would be especially adversely affected.

3.2.5.2. Mortgage approval for 3D-printed houses

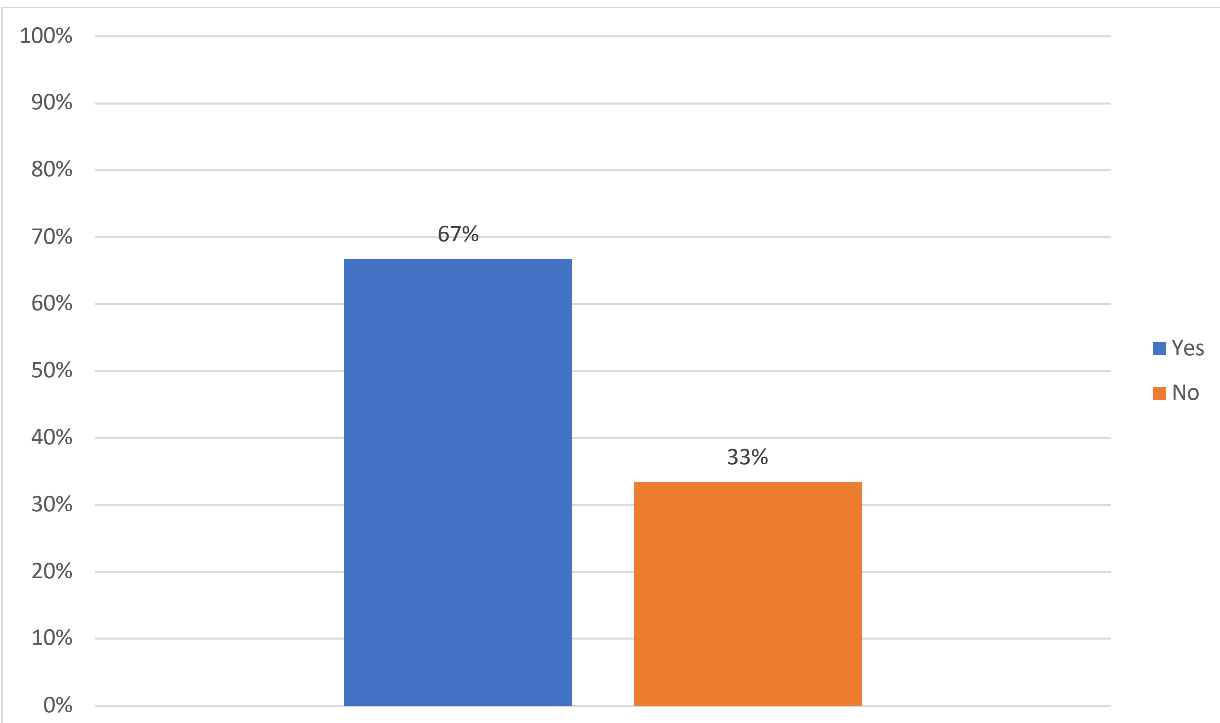


Figure 3.21: Mortgage approval of 3D-printed houses

Sixty seven percent of the respondents believed that banks would agree to finance 3D-printed houses "if the durability could be proven". A few respondents believed that banks were inflexible and would not finance 3D-printed houses. They also stated that this technology has not yet been proven in South Africa as another reason why banks would be hesitant to finance 3D-printed houses.

Following confirmation of the viability of 3D-printed houses, additional research should be done to determine the acceptance levels of 3D-printed houses by other stakeholders such as municipal house inspectors and the NHBRC.

3.2.5.3. Municipal approval for 3D-printed houses

Fifty six percent of respondents stated that municipalities would approve 3D-printed houses. Some respondents believed that 3D-printed houses would necessitate amendments to the current municipal by-laws and building codes. For example, detailed guidelines will have to be provided for how the electrical and plumbing sections ought to be placed within the 3D-printed house. Municipal approval might also include an assessment on environmental and structural impact of 3D-printed houses.

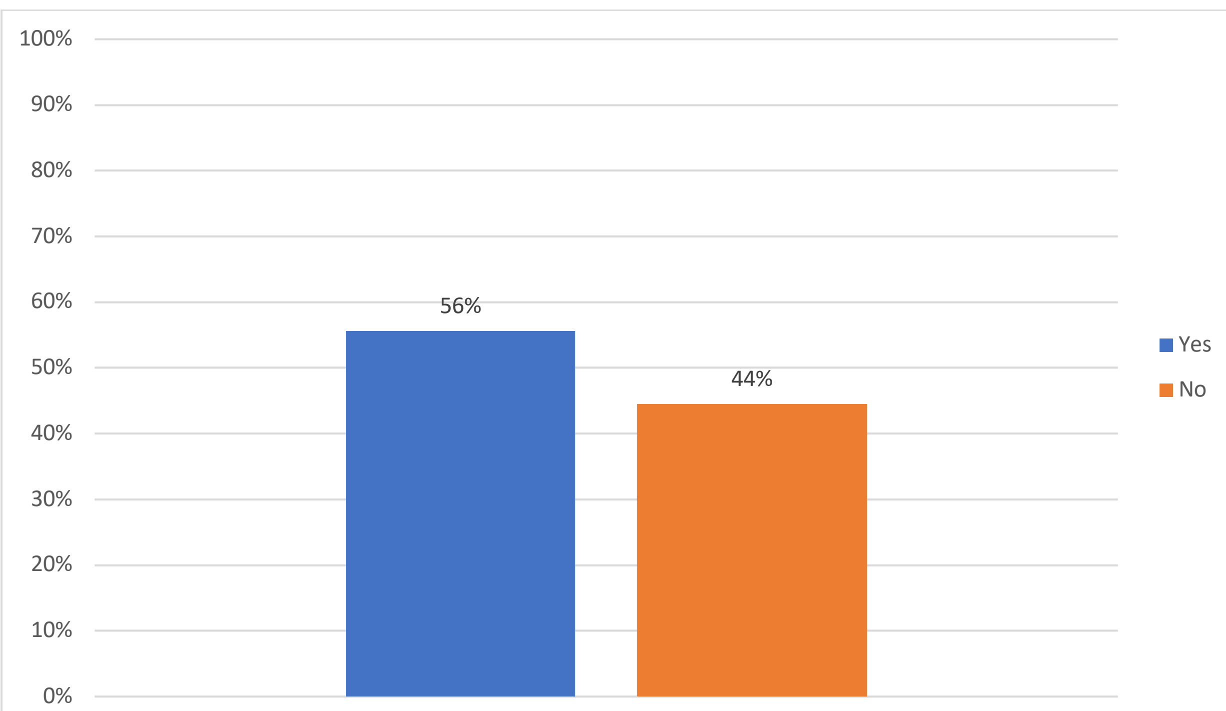


Figure 3.22: Municipal approval for 3D-printed houses

Indications are that changes will have to be made to building codes and municipal requirements. Regulatory aspects that will potentially be affected by 3D-printing of houses needs to be further researched.

3.2.5.4. Living in 3D-printed houses

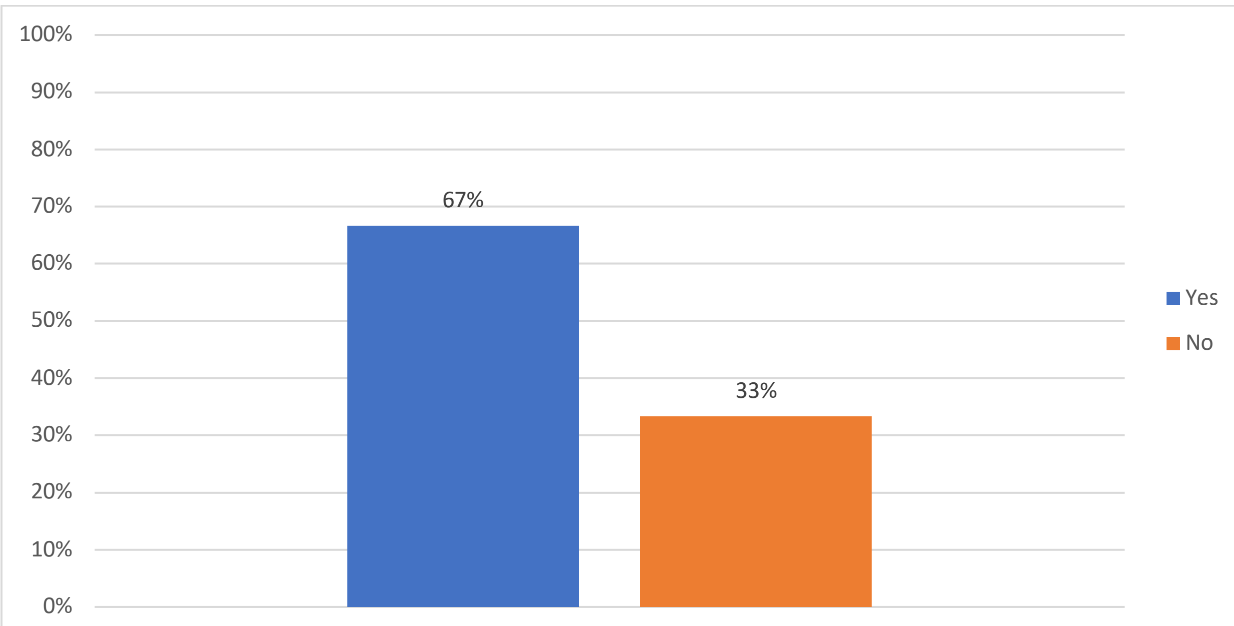


Figure 3.23: Living in 3D-printed houses

Sixty seven percent of the respondents agreed that they would be happy to live in a 3D-printed house. They found the idea exciting and technologically advanced. They stated that this new technology could mean fewer defects and better insulation, which could save money on repairs and heating or cooling. A small number of respondents was sceptical about the durability of a 3D-printed house and they stated that they would first need to research it better before considering living in one.

4. CONCLUSION

In South Africa, 3D-printing of houses is still in its infancy stage of development and understanding. Most of the respondents had some rudimentary understanding of 3D-printing. This was through social media and television. Houses that are 3D-printed seem to excite respondents. Their interest is perked by the technology's many possibilities.

More than 78 percent of respondents indicated that square, rectangular and circular shapes are acceptable as 3D-printed houses. The majority of them also stated that 3D-printed houses would be easier, cheaper, faster, better and safer than conventionally built houses. As reasons, they cited less human error, the building materials used would be of the same standard throughout the projects and that it would much faster to 3D-print a house. Sixty-seven percent of the respondents agreed that they would be happy to live in a 3D-printed house. However, a fair number of them said that they would need assurance that a 3D-printed house is as structurally sound and durable as a conventionally built house before they would agree to live in it.

Many respondents stated that professionals and artisans that could be affected by 3D-printing of houses included bricklayers and plasterers (because they would not be needed on site), as well as structural engineers and architects (because they might only be needed in the beginning of a project).

Respondents were generally concerned that job losses will occur with the advent of 3D-printed houses, with bricklayers potentially the worst affected group. Furthermore, some of them questioned the durability and viability of 3D-printed houses. Municipal approval of 3D-printed houses was also a worry as it was felt that by-laws, procedures and building codes have to first be amended.

Some respondents require more research and demonstration to be done before they would be completely satisfied about the efficacy of 3D-printed houses. Still, they did consider this technology exciting and are looking forward to experiencing it themselves.

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