# Modular 3D printing construction: towards affordable, adjustable and climate-resilient housing

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## Key Messages

- Modular 3D-printing construction technology (M3DP) is a novel technology that combines modular construction and 3D-printing to address the backlog of affordable houses in cities of developing countries vulnerable to climate risks.
- M3DP has the potential to create adjustable, affordable, and climate-resilient housing for low-income citizens.
- Applied to the South African context, key factors for successful implementation of M3DP include: social acceptance of M3DP projects, local M3DP expert availability, and thermal insulation needs included in design.
- Core recommendations are to further develop dry and wet joints, create industry standardized building criteria, and design climate resilient structures that include bio-based materials.

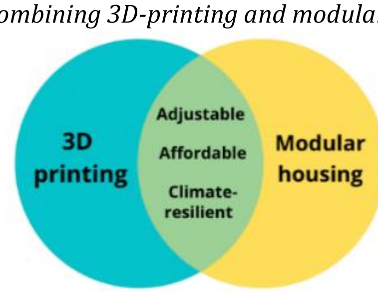
## Background

By 2050, 68% of the world's population is expected to be living in cities, and most of this increase will take place in **developing countries**.[1] The rapid **urbanization** in cities of developing countries is concentrated amongst the poorer spectrum of the population.[2] Increasing urban population and households' size require adjustable functions for low-income housing. Citizens living in **relative poverty** are one of the most vulnerable groups to climate change. Cumulatively amplifying the need for **adjustable**, **affordable**, and **climate-resilient** housing.[2]

3D-printing technology (3DP) is a novel construction practice in a 36-billion-dollar industry by 2025.[3] Also called additive manufacturing, the technology used 3D data to manufacture products such as houses.[4] The construction process is fast, flexible in design, and requires minimal labor and materials. It has the potential to facilitate adjustability to the growing population, is affordable to those most in need, and is climate-resilient to ongoing climate change in cities of developing countries. Currently, 3DP companies are engaging with modularity. Modular construction is a **prefabrication** construction process where buildings are constructed in separate modules in an off-site factory, to be assembled on-site.[5] Modular construction became more prevalent in response to the COVID-19 crisis.[6] It shows potential to create adjustable, low-cost, and resource-efficient housing because it reduces material waste, disruption at construction sites, and overall energy use in buildings.[7,8] Developing modular 3D-printed construction technology (M3DP) entails that house modules are 3D-printed separately and assembled on-site. It combines the cost-efficiency and on-site construction of 3DP houses with the reusable and adjustable qualities of modular construction. In Annex 2, M3DP is defined in further detail.

M3DP could contribute to the construction of adjustable, affordable, and climate-resilient houses (figure 1) and the Sustainable Development Goals (SDG) (see Annex 3). However, this assumption requires further contextual research of cities in low-income countries. This brief aims to critically assess M3DP's contribution to realize adjustable houses for a growing population, affordable to lower-income citizens, and climate-resilient to withstand increasing climate risks in cities in developing countries for the coming decade (the research questions can be found in Annex 4). This is operationalized through a horizon scanning of M3DP and a case study of cities in South Africa (SA). The outline and motivation for the methodology can be found in Annex 5. The next sections delineate the adjustability, affordability, and climate-resiliency of M3DP, followed by the results of a case study of SA. Future trends of M3DP are illustrated in Annex 6. Lastly, a list of recommendations for urban policymakers, investors and engineers is presented.

*Figure 1. Combining 3D-printing and modular construction*




## Adjustable design

Adjustability refers to the house's capacity to accommodate changes in urban population, household size, and the functions of the house's spaces. M3DP technology creates adjustable houses in the following ways:

- M3DP creates **expandable** houses: houses are constructed in modules, and more modules can be added to create more space when needed.[9]
- M3DP creates houses that are **malleable**: after construction, the house modules can be reassembled to create different rooms. This is helpful when the household expands and more bedrooms are needed. The current state of the 3DP technology allows for houses to be built up to 2 stories high.[3]
- M3DP houses are **movable**: after construction, the houses can be disassembled and transported to a new location. The capacity to relocate a house makes the structure more flexible when confronted with natural hazards.[10]

Through its expandability, malleability, and movability, M3DP provides an innovative way towards adjustable housing. In current 3DP construction, **wet joints** are used between components, permanently conjoining them, and impeding the disassembly of the house. By adding a modular construction technique, modules can be attached using **dry joints** instead. The **envelope system** (figure 2) is an example of a dry joint system, whereby M3DP houses are designed for disassembling.

In coming years, M3DP research is developing smaller printers and different **nozzle** sizes to construct smaller, modular concrete products, as well as to create higher structures in modules (see Annex 6).[11–13]

*Figure 2. M3DP envelope design11*

## Affordable housing

The house's affordability depends on construction costs, labor costs, and financial incentives such as subsidies and grants. M3DP decreases the cost of the house in the following ways:

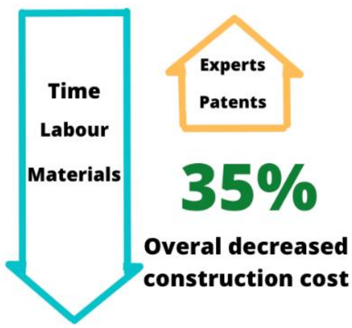
- M3DP allows for a 35% decrease in total construction costs through increased building efficiency.[3]
- The labor costs associated with M3DP are decreased and diversified due to the few people necessary for the construction, varied workload, and faster construction time, despite the labor cost per operator being higher.[14–16]
- The training and development of skills are not expected to carry high costs as the operation of the machines does not require advanced skills.[17]
- The material usage is decreased by 40% compared to conventional construction methods, resulting in pollution reduction.[3,14,18]

Despite these advantages, there are also aspects of M3DP that increase the costs of the houses:

- The material costs are currently higher than conventional construction materials. However, this is expected to decrease with the incorporation of bio-based materials.[15]
- Since M3DP cannot create large-scale infrastructures, the initial capital investment necessary to realize construction is currently too high to create affordable houses in developing countries.[19]
- Due to its novelty, the highest investment costs of M3DP lie in research and development. Since this technology is not yet produced on a large scale, investment risks are high, which prevents institutions with low capital to implement the technology.[3]

In recent years, new material mixes were created using local materials so users of M3DP in developing countries could become independent of foreign companies.[20] This increases the affordability of the technology, as material import costs will decrease.[20] Moreover, the increasing popularity of M3DP anticipates an increase in investments, making M3DP houses more affordable in the long run.[15,21,22] Lastly, the expected innovation of dry joints allows flexibility of the exterior – increasing opportunities for low-cost maintenance and growth.

*Figure 3. Relative cost reduction of M3DP*




## Climate-resilient structures

A climate-resilient house can withstand natural hazards that result from climate change, such as floods, droughts, and extreme temperature fluctuations. M3DP shows potential to build climate-resilient houses in the following ways:

- M3DP technology can provide strong and flexible structures that allow temperature control with a minimum of air conditioning by incorporating air bubbles in the printing of cementitious mix to improve thermal insulation and acoustic absorption.[4]
- M3DP allows for innovative structure design that can integrate climate-resilient features. For example, a honeycomb foundation can be made from reinforced concrete with air pockets that allows houses to float up to almost three meters in case of flooding.[4,10]
- To create climate-resilient structures, researchers are looking into the implementation of **bio-based materials** (e.g. hemp or mycelium) in M3DP for proper insulation of houses, increased fire resistance, improved heat control, and increased structural strength (see Annex 6).[3,23]
- Steel reinforcement or inclusion of bio-based materials into the concrete mix has proven to increase the **ductility** of concrete.[24]

Adding bio-based materials for structural reinforcement increases climate resilience, but also contributes to climate mitigation by storing carbon in the form of hemp.[3] As concrete is currently responsible for 8% of global greenhouse gas emissions, there is a need to rapidly decarbonize the emissions of the industry.[25]

## Modular 3D-printed construction in South Africa

Housing in SA is a pressing and complex issue due to apartheid and the country's colonial legacy.[26,27] Background information on housing in SA can be found in Annex 5.3.1. In the following sections the adjustability, affordability, and climate-resilience of M3DP in the context of SA are discussed.

**Adjustability:** In SA, the housing sector is unable to accommodate the current and growing demand of its increasing population. Built homogeneously, most houses are unfit for the diversity and fluctuation of household size. The adjustability of M3DP counters the current one-size-fits-all strategy and accommodates growing households with expandable, malleable, and movable houses.[3,28,29] Experts in SA state that the inclusion of the local population in the creation of the houses increases the social acceptability of the project.[26,27,29] However, SA housing regulations limit the implementation of M3DP since houses cannot legally be moved and the necessary materials are not yet on the list of permitted building materials.[9,29,30]

**Affordability:** A main barrier for affordable M3DP construction in SA is the lack of investment in standardized research and development, which prevents it from meeting local housing codes.[3,29] For M3DP to facilitate large-scale apartment buildings, stronger construction materials need to be developed.[33,26,29] Moreover, the SA market of M3DP is currently small due to the high patenting costs and the fact that most experts are situated in Europe. Thus, expert availability is low and labor costs high.3 Additionally, government incentive for M3DP houses is lacking because of low social acceptability and vandalism due to the newness of M3DP and conservative construction cultures.[3,31,32] Diverse funding support from international governments, multilateral support, and private investors could help the national government bear the investment costs that M3DP requires as it is unlikely they are able to do this alone.[26,27] Lastly, the decrease in labor of M3DP construction perpetuates lower acceptance as it increases unemployment.[26,27] It is therefore necessary to ensure that M3DP in developing countries does not perverse job equity and workers retrained.[26]

**Climate-resilience:** M3DP has the potential to build houses that withstand droughts, floods, and fires, which are the most prevalent climate risks in SA.[27] Combined with bio-based materials such as hemp fiber, M3DP houses become more fire-resistant.[3] M3DP creates custom designs like stilts to overcome flooding,[3] as well as honeycomb structures to make houses float.[4,10] When it comes to temperature regulation, M3DP needs traditional methods to include insulation.[21] However, by creating space for insulation materials in the structures, M3DP allows for this process to be faster than it would be in conventional construction, improving the speed of housing.[12]

**South Africa trends:** Though M3DP has yet to be implemented in SA, 3DP has been successfully implemented in African countries. An example of an affordable 3DP housing project is the 14Trees Foundation recently announced Mvule Gardens in Kenya.[22,33] Moreover, in collaboration with CyBe, a pilot project will be launched in March 2022 to construct one of the first 3D printed houses in SA.[20] These trends indicate that 3DP already is a viable option to contribute to the housing backlog in the country. Experts agree that combining 3DP with modular construction into M3DP could improve the social acceptability of these houses, by giving South Africans the opportunity to adjust their own homes.[26,29,32] Lastly, SA's Department of Science and Innovation recognized 3DP as a key area of the digital revolution, expressing a need for initializing the development of an educational curriculum to improve local 3DP skills.[34]

## Recommendations

M3DP can contribute to adjustable, affordable, and climate-resilient housing for low-income people in developing cities. To further these goals, the following points are recommended:

1. Invest research in **3DP** to fund the development of **dry joints** to improve the **expandability, malleability,** and **adjustability** of the houses.
2. Create industry standards criteria for M3DP material testing through collaboration between engineers and construction practitioners to accelerate the uptake of M3DP.
3. Integrate **bio-based materials**, such as hemp, into the printing material to improve structural reinforcement, lower materials costs, and reduce carbon footprint.
4. Print design with climate-resilient characteristics in mind (e.g., incorporate honeycomb air pocket design in the walls to allow floatation potential during floods).
5. Recognize social housing status for M3DP construction projects to obtain external funding for the delivery of affordable houses in developing countries (e.g., social housing certification schemes).
6. Increase social acceptability and trust when introducing M3DP construction projects to low-income communities through early engagement with end-users and providing examples for community use (e.g., public restroom, playground, bridges, schools, or supermarkets).

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# Annex

## ANNEX 1. Glossary

**Adjustability**: The active flexibility of a house to accommodate the needs of its inhabitants over time by being expandable, malleable, and movable.[35]

**Affordability**: Equal economic access to all, especially the poor and the vulnerable.[36]

**Bio-based materials**: Substances made from living organisms or their by-products.[37]

**Carbon footprint**: The amount of carbon dioxide emissions associated with all the activities of a person or entity.[38]

**Climate resilience**: Ability to anticipate, reduce, accommodate, or recover from the effects of weather events related to climate change in a timely and efficient manner.[39]

**Developing countries**: Nations that have a score less than .80 in the Human Developing Index.[40]

**Dry joint**: Link between two or more components of the house which does not have any binding material.[3]

**Ductility**: The extent to which a material or structure can undergo large deformations without failing.[41]

**Envelope system**: An innovative prefabricated building system. The design uses the potential of 3D printing for prefabricated components and consists of precast elements that can be printed on-site and assembled by using completely dry links. The envelopes can be easily disassembled, reused, or recycled.[11]

**Expandability**: The ability to add to a house or structure.

**Housing backlog**: The under-provision in housing that has accrued against previous development plan targets.[42]

**Housing codes**: Minimum standards adopted by regional administrations to govern the construction of buildings.[43]

**Informal Urban Settlements (IUS):** Residential areas where inhabitants have little security of tenure for the land or dwellings they live in, neighborhoods lack basic services and infrastructure, and housing does not comply with planning and building regulations.[44]

**Malleability**: The capability of an object to be altered in its construction.

**Modular 3D-Printed construction technology (M3DP):** The combination of 3DP technology and modular building technique (see annex X for further explanation).

**Movability**: The capability of an object to be moved and located elsewhere.

**Nozzle**: A component of a 3D printing machine that deposits the printing material into the build area.[45]

**Relative poverty**: Poverty that changes depending on the context: relative poverty is present when a household income is below the median income in a country.[46]

**Prefabrication**: A building technique where parts have been made separately and put together on-site

**Urbanization**: The process of an increasing percentage of the population living in cities.[47]

**Wet joint**: Link between two or more components of the house that involve a binding material.[3]

## ANNEX 2. Modular 3D-printing construction technology

Modular 3DP construction technology (M3DP) is a novel combination of two technologies: modular construction and 3DP construction.

Modular construction is a prefabrication method of construction. Prefabrication uses components made off-site in a factory and transports them to be put together on-site. Prefabrication offers opportunities for both environmental and economic performance.[48] Through prefabrication, modules or pods that are essentially three-dimensional or volumetric elements are built and put together, creating resilient, low-cost, and resource-efficient housing. Modular construction provides the houses with the flexibility to be adapted, modified, or disassembled into separate components that can be reused or deconstructed for recycling.[8,48] Image A1 shows the assembly of a modular house.

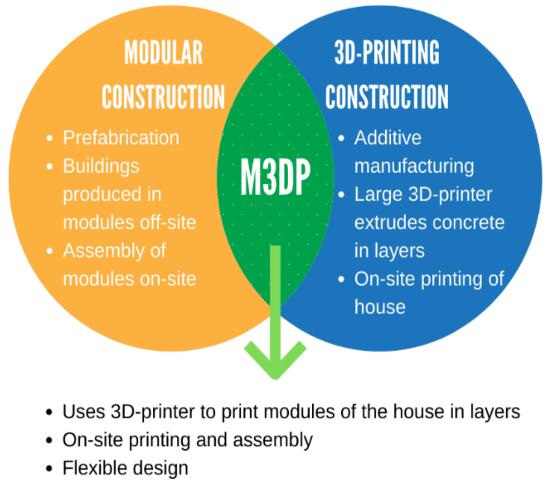
3DP construction technology is also called additive manufacturing. Conventionally, 3D-printed houses are constructed on-site by large 3D printers that extrude concrete, plastic, or other building materials through nozzles. Through this, a house is constructed layer by layer.[7,49] Image A2 shows the construction of a 3D-printed house.

*Image A1 (left): Assembly of a modular house.[50]*

*Image A2 (right): Using a 3D-printer to construct a house.[51]*

Combining the two technologies into M3DP marries the customizability, cost-efficiency, and on-site construction of 3DP houses with the adjustable qualities of modular construction. M3DP entails that the modules of the house are printed and assembled on-site. Figure A1 shows a schematic representation of the combination of modular construction and 3DP construction into M3DP. M3DP could contribute to the construction of adjustable, affordable, and climate-resilient houses.

*Figure A1. Schematic representation of the properties of modular & 3DP construction, combined into M3DP*




## ANNEX 3. Relevant Sustainable Development Goals (SDGs) for M3DP

**Table A1. SDGs and their link to M3DP**

| No. | SDG | Link |
|---|---|---|
| **3** | Good health and well-being | Experts have suggested that adequate housing should be treated as a human right since it allows people to access a better quality of life. The COVID-19 pandemic showed the importance of having spaces to quarantine and follow hygiene measures. Combining 3D printing and modular housing has the potential for policy makers, spatial planning institutions, and the construction industry to collaborate in creating sanitary spaces for at-risk communities at a higher speed. |
| **9** | Industry, innovation and infrastructure | M3DP has a relatively higher construction speed, lower material, labor, and transport use, reduces overall waste due to higher climate resilience and modularity. However, due to its automation process, it changes the labor profile drastically and is extremely progressive for the conservative nature of the construction market. |
| **10** | Reduced inequalities | Accessibility to adequate housing drastically impacts the overall equality of living conditions within a society. The construction of affordable, adjustable, and climate-resilient houses therefore impacts the overall level of equality amongst citizens. |
| **11** | Sustainable cities | The construction industry has one of the most pollutant and non-reusable products cycles. The combination of these technologies has the potential to revolutionize the collaboration in the construction process of sustainable and reusable houses in slums. |
| **12** | Responsible consumption and production | As aforementioned in SDG 11, the construction industry as it stands is non-reusable in its material use. 3MDP can be revolutionary when the technology becomes developed to the extends whole houses can be moved and relocated. It moreover allows for modules to be replaced without harming the integrity of other modules. |
| **13** | Climate action | Under the improvement on climate action falls the improvement towards climate resilience. 3MDP contributes to the facilitation of houses to withstand floods, string wind, hot and cold temperatures. The customisability of the printer aspect makes the capacity of this construction process infinite. |

## ANNEX 4. Research aim and questions

### *4.1. Research aim*

The research aims to critically assess the extent to which modular 3D-printed construction technology could contribute to adjustable, affordable, and climate-resilient housing in developing cities.

### *4.2. General research question (GRQ):*

To what extent can modular 3DP construction technology contribute to low-income housing for inhabitants of informal urban settlements in developing cities, in terms of adjustability to accommodate rapid urbanization, resilience to climate-related shocks, and affordability for these communities in the coming 10 years?

### *4.3. Sub-research questions (SRQ):*

1. In which ways can modular 3D-printed construction technology contribute to the building of housing that can adjust to rapid urban growth by 2030?
2. In which ways can modular 3D-printed construction technology contribute to the building of climate-resilient houses by 2030?
3. In which ways can modular 3D-printed construction technology contribute to the building of affordable housing for the local population by 2030?
4. Through a case study of SA, what is the potential of modular 3D construction tech to contribute to adjustable, climate-resilient, and affordable low-income housing for inhabitants of informal urban settlements by 2030?

## ANNEX 5. Methodology

### *5.1. Operationalization of concepts*

Table A2 shows a list of concepts used, and how these were operationalized into indicators as a base of the research. These indicators were operationalized as codes applied in a qualitative analysis using the program Atlas TI.

| **Table A2: Operationalization of concepts into indicators and codes** | |
|---|---|
| *Concept* | *Indicators/codes* |
| Adjustability | **Speed of construction**<br>the time it takes to construct a house |
| | **Movability of house**<br>the capacity of the constructed house to be moved elsewhere |
| | **Movability of house parts**<br>the capacity of parts of the constructed house to be moved elsewhere |
| | **Malleability of house**<br>the capacity of the constructed house to be altered |
| | **Modularity of house**<br>the capacity of a house to be made in modules |
| Climate resilience | **Withstand climate**<br>shocks related to climate change capacity of a house to survive a climate change |
| | **Withstand flooding** |

| | |
|---|---|
| | capacity of a house to survive floods |
| | **Withstand earthquakes**<br><br>Capacity of a house to survive an earthquake |
| | **Withstand fires**<br><br>Capacity of a house to survive a fire |
| | **Withstand wind**<br><br>The capacity of a house to withstand strong winds |
| | **Withstand high temperatures**<br><br>Capacity of the foundation of a house to withstand extreme heat |
| | **Withstand low temperatures**<br><br>Capacity of the foundation of a house to withstand extreme cold |
| | **Withstand droughts**<br><br>Capacity of the foundation of a house to withstand droughts |
| Affordability | **Investment**<br><br>The amount of money (expected) invested by external investors in technology |
| | **Cost construction materials**<br><br>Cost of the materials to construct the house |
| | **Cost maintenance materials**<br><br>Cost of the materials to maintain the house |
| | **Cost construction labor**<br><br>Costs of labor needed to construct the house |
| | **Cost maintenance labor**<br><br>Costs of labor needed to maintain the house |
| | **Cost land tenure**<br><br>Cost of land to construct a house |
| | **Rental Subsidies**<br><br>Money from the government to aid renters to pay rent |
| | **Construction subsidies**<br><br>Money from the government to aid construction costs |
| | **Expert cost** |

| | |
|---|---|
| | The money needed to hire experts |
| Overarching concepts | **South Africa**<br><br>South Africa related remark or argument |
| | **Technology**<br><br>a remark or argument on 3D printing AND/ OR modular 3D printing |
| | **Recommendation**<br><br>a remark or argument useful for the recommendation. |
| | **Now**<br><br>Indicators relevant for current state/time |
| | **Short future**<br><br>Indicators relevant for the coming 1-5 year |
| | **Long future**<br><br>Indicators relevant for the coming 5-10 years |
| | **Housing market regulations**<br><br>Regulations in the housing market (e.g., rental cap, rent stabilization measures, rental relief, etc.) |
| | **Housing regulations**<br><br>Laws and policies on housing construction |
| | **Technology regulations**<br><br>Laws and policies on technology |
| | Expert's regulations<br><br>Laws and policies on experts |
| | **Expert availability**<br>The expert labor availability |
| | **Population growth**<br>Increase of a population in a given setting |
| | **Family growth**<br>Increase of a family (in the context of housing) in a given setting |
| | **Social acceptability**<br>The aggregate social acceptance of a certain variable by a certain group |

### *5.2. Horizon scanning*

To answer SRQ 1, 2, and 3 a horizon scan was performed. Horizon scanning is a systematic process that looks at early signs of any potential developments in an area of interest. The goal of horizon scanning is to detect new trends, new drivers of change, weak signals, and discontinuities. This methodology is used for the early detection of phenomena that could potentially have an impact on society.

Horizon scanning can help policy makers in using or mitigating the upcoming technologies to make decisions with the most positive impact.[52] Because the combination of modular construction and 3D-printed construction is new, horizon scanning could help to create a holistic view of its future. As the terms of reference ask for technologies in a post-covid world, horizon scanning's anticipatory character fits the purpose of the brief.

*5.3. Case study of South Africa*

A case study is a thorough examination of a phenomenon in a specific context to obtain information that can lead to interpretations of the studied phenomenon or to make generalizations between similar groups.[53] A case study approach was used to analyze the enablers and barriers to the use of modular 3DP construction technology in the context of South Africa and answer SRQ 4. This context was selected because major population growth is expected in Africa. In the context of Africa, 62% of the population lives in informal urban settlements.[54]

*5.3.1. Background of housing in South Africa*

South Africa (SA) is a country with an expected population growth of 10% in the coming 10 years, a current approximate poverty rate of 55%, and increased flooding and drought risk.[27] Rapid urbanization in South Africa is characterized by the expansion of informal urban settlements (IUS).[2] Inhabitants of IUS are one of the most vulnerable groups to climate change, amplifying these people's needs for adjustable, affordable, and climate-resilient housing.[2]

The causes of the backlog in housing in SA stem from apartheid and the country's colonial legacy.[26,27] Especially in Southern Africa, housing is a political tool, because it was a way in which the state excluded large chunks of society.[26] Moreover, the conventional construction industry commercializes the supply of houses, excluding people on the ground that need it most.[29] Furthermore, most low-income housing constructed by the cities of SA is built far from the economic centers of the cities.[27] As a result, many people remain in IUS because they are closer to city centers.[27] Lastly, COVID-19 had a major impact on SA's economy, increasing people living in poverty by 2 million.[55] It is therefore crucial that solutions to the housing backlog in SA address more than just the construction of a house – in addition, it should address the social roots of the problem.[26,29]

Depending on bylaws and plot size, it is allowed to extend your house in SA.[26] Cape Town and Johannesburg municipalities are open to innovative ideas when it comes to expanding the house. However, when it comes to practice, the main trend in house extensions is backyarding: this is the construction of shacks in the backyard of a formal house.[26,56] The main reason that house extensions are built informally is because the application for a permit is a lengthy and costly process.[26]

South Africa's Department of Science and Innovation (DSI) published a ''National digital and future skills strategy South Africa'' in 2020.[34] In this strategy, 3DP is described as a key area of the digital revolution. The need is expressed for initializing the development of an educational curriculum about 3DP to improve the skills of the local population in this field. Thus, showing the priority of the government to further develop this technology in the coming years and counter the potential loss of job opportunities as a result of using M3DP.

*5.4. Data collection and analysis*

To collect the data necessary to answer the research questions (Annex 2), two forms of data collection were used. First, a systematic literature review was used to summarize the knowledge from theoretical literature to provide a comprehensive understanding of our topic.[57] Recent literature was used (starting from 2017) to gain insight into modular 3D printing construction technology, its developments, and the newest trends. Table A3 shows the search terms that were used.

**Table A3: Search terms used per sub-research question (SRQ)**

| ***SRQ*** | ***Search terms*** |
|---|---|
| In which ways can modular 3DP construction technology contribute to the building of housing that can adjust to rapid urban growth by 2030? | Adaptability + 3DP house |
| | Adjustability + modular + 3DP |
| | Malleability + modular + 3DP + house |
| | Speed construction modular 3DP house |
| | Trends+3DP+modular |
| In which ways can modular 3D construction technology contribute to the building of climate-resilient houses by 2030? | Climate resilience modular construction |
| | Climate resilience 3DP house |
| | Climate resilience house |
| | Fire resistant+3DP+house+modular |
| | Flooding+3DP+modular |
| | Insulation+3DP+modular |
| | Climate+change+risks+2030 |
| In which ways can modular 3DP construction technology contribute to the building of affordable housing for the local population by 2030? | Cost-benefit modular construction |
| | Prefab costs |
| | 3DP+affordable+housing |
| | Modular+affordable+housing |
| | 3DP+modular+affordable |
| | 3DP+cost+patents |
| | 3DP+cost+materials |
| Through a case study of SA, what is the potential of modular 3D construction tech to contribute to adjustable, climate-resilient, and affordable low-income housing for inhabitants of informal urban settlements by 2030? | South Africa modular construction |
| | South Africa social housing |
| | South Africa 3DP houses |
| | South Africa+COVID-19+housing |
| | South Africa+housing+needs |

Additionally, semi-structured interviews were conducted with experts. The names, expertise, and contact information of these experts can be found in Annex 7. In semi-structured interviews, the interviewer has a guide with questions on several topics, but the emphasis lies on how the interviewee frames and understands the content of the questions, leaving room to stray from the guide.[58] Two members of the team were present during the interviews. One member of the team was responsible for interviewing while the other member took notes and oversaw recording. The recording of the interviews allows for future referencing and facilitate transcription.

Different experts were interviewed in compatible fields such as 3D printing construction, sustainable housing, modular construction, and experts who could provide insight concerning urban informal settlements. Experts were found through searching online (search engines, LinkedIn). Furthermore, all contacted experts were asked to recommend other potential interviewees. This way, researcher bias was minimized, and experts could be reached beyond the research teams' perspective. Lastly, before each interview was conducted, we provided the interviewees with an informed consent form. All interviewees provided us with either written or verbal consent to the terms of our research, allowing us to use the data from the interviews for our research.

After collecting the data (interview transcripts and literature), the program Atlas TI was used to analyze our sources. Atlas TI supports qualitative analysis of text by allowing researchers to manage, visualize and report from the collected data. Specifically, codes were created based on table A3.

### *5.5 Limitations of the research*

This research has several limitations and concerns.

- There's a lack of secondary data on the research and literature on modular 3D printing (M3DP) technology due to its new nature.
- This research is limited in its sample profile; the scope of the case study specific interviews did not incorporate South African government officials and inhabitants of low-income urban houses.
- The extent to which the local perspective is representative in the data, analysis, and conclusion is lacking. This withheld the incorporation of certain case-specific factors important to establish a holistic view of South African's house needs such as safety; exemplified in incorporating the capacity for the houses to be bulletproof due to gun violence.
- The biases of the interviewees, although accounted for during the analysis, have bound the data to be representatives of those who participated. Due to the lack of governmental and local interviewees, the findings are geared towards the bias of technological experts and market actors.
- The methodology limited the research; the indicator of 'earthquakes' was unaccounted for in the research, due to its ill application to the case study. It was however a frequently reoccurring topic on the topic of climate-resilient housing. Therefore, further research is suggested to focus on the capacity of M3DP to withstand earthquakes.
- The methodology did not operationalize indicators on the socio-political factors that impact the housing market in the SA case study. This limits the understanding of important identified obstacles and opportunities to the incorporation of M3DP such as social acceptability and expert availability.

## ANNEX 6. Trends in modular 3DP construction technology (M3DP)

**Table A4 Trends in M3DP for the coming 10 years**

| | **Current state** | **In 10 years** |
|---|---|---|
| Adjustability | On-site building of walls and structural system only.[29,32]<br>Size of 3D printers limits construction to one- or two-story buildings.[12]<br>Wet joints between components make it unfeasible to move and/or disassemble.[3] | Construction of smaller prefabricated structures, furniture, and piping by using smaller printers and different nozzle sizes.[13]<br>Smaller 3D printers that can be stacked on top of each other to create higher buildings.[12]<br>Dry joints between the components of the houses.[3] |
| Climate resilience | Material mix composed of a minimum of 40% concrete which does not provide good insulation and a layer of insulation material must be added.[3,21,59]<br>Use of concrete because of best-known capacity to withstand an extreme climate.<br>Construction industry is responsible for 38% of global emissions. | Implementation of bio-based materials (hemp, mycelium) in the mix, used for insulation of houses.[3,23]<br>Use of mixes without concrete (polymers) that are stronger than concrete and can withstand a wide range of natural hazards.[59] |
| Affordability | Expensive due to high costs of machines and materials due to industry dependency.[12,20,29]<br>High risk for investors as M3DP is not well-known and its social acceptability is questionable.[20,21,32,33]<br>Insufficient government incentives to support the development of M3DP.[7] | Creation of mixes with local materials to become independent of foreign companies.[20,59]<br>Higher rates of investment as the popularity of M3DP grows will lead to a decrease in its costs.[7,15,21,22] |

## ANNEX 7. List of interviewed experts

**Table A5 Name, function, and topics discussed per interviewee**

| **Nr.** | **Name** | **Institution** | **Position** | **Country** | **Topic** | **Date** |
|---|---|---|---|---|---|---|
| 1 | Dr. Khululekani Ntakana | University of Johannesburg | Lecturer | South Africa | 3D printing | 20-Nov-2021 |

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| 2 | Alfredo Brillembourg | Urban-Think Tank | Co-Founding partner | United States of America | Modular building | 24-Nov-2021 |
| 3 | Darlington Sibanda | University of Cape Town | Postdoctoral Research Fellow | South Africa | South African context | 25-Nov-2021 |
| 4 | Zeeshan Yunus Ahmed | University of Eindhoven | Ph.D. Researcher (3D Concrete Printing) | The Netherlands | 3D printing research | 25-Nov-2021 |
| 5 | Elias Hernandez Valera | Wageningen University & Research | Ph.D. Candidate (Urban Economics) | The Netherlands | 3D printing research | 26-Nov-2021 |
| 6 | Refilwe Lediga | University of Johannesburg | Ph.D. Candidate (Artificial Intelligence & 3D Concrete Printing) | South Africa | 3D printing researhc | 27-Nov-2021 |
| 7 | Salah Eddinne Bouzid | COBOD International | Sales and Marketing | Denmark | 3D printing industry | 20-Nov-2021 |
| 8 | Peter Paul Cornelissen | Weber-Beamix | International 3D Project Manager | The Netherlands | 3D printing industry | 03-Dec-2021 |
| 9 | François Perrot | 14Trees Foundation | Managing Director | South Africa | Affordable housing in Africa | 03-Dec-2021 |
| 10 | Patience Mguni | University of Copenhagen | Governance work package leader | South Africa | South African context | 06-Dec-2021 |
| 11 | Juergen Mayer | Peri | Innovation manager | Germany | Modular building | 06-Dec-21 |
| 12 | Oliver von Malm | StartSomewhere | Founder, Director | Germany | Modular building | 06-Dec-21 |

ANNEX 8. Alternative technologies to M3DP

**Table A6 Name, explanation, and more information on alternative technologies**

| Name | Explanation | Further information can be found at |
|---|---|---|
| Twistblocks[60] | Twistblocks offers easy-to-build concrete housing solutions. The project is developed by Start Somewhere, a German organization with over 10 years of experience in development cooperation in one of the largest informal settlements in Africa: Kibera, Nairobi (Kenya). German building organization Peri Germany, one of the world's leading manufacturers of formwork and scaffoldering, provided the moulds for the Twistblocks.<br><br>The project addresses two main challenges in the global south. First, the living conditions of people in informal environments, including lack of jobs, no secure land tenure, and unsafe and unhealthy homes. Secondly, it addressed the need of humanitarian organizations for quick and affordable building of schools and hospitals with a certain safety standard.<br><br>The Twistblocks are hollow, lightweight concrete blocks that can be assembled and disassembled by hand as a modular, mortarless plug-in system.<br><br>The project allows for private home ownerships since the Twistblocks can be easily dismantled and reused elsewhere.<br><br>This project contributes to adjustable, re-usable, affordable, and fireproof construction of buildings in informal settlements<br><br> | https://www.startsomewhere.eu/en/ |
| UBU sandbag houses [26] | The UBU houses require a combination of Sandbags and Ecobeams. Ecobeams consist of steel and timber which form the frame. Polypropylene sandbags are then stacked, and a fiberglass mesh is added before everything is plastered over.<br><br>The houses are fire-proof, bulletproof, have high thermal and acoustic insulation, and have an eco-friendly design that results in reduced reliance on fossil fuels. This building technique is 40% cheaper than conventional brick buildings. Lastly, it is a self-build technology and facilitates adjustability as the technology can be used to build a house incrementally. | https://www.ubu.bz/how-we-build |

| | | |
|---|---|---|
| |  | |
| Empower hack[29] | Empowerment shacks are low-income houses developed by the Urban Think Tank (ETHZ) and NGO Ikhayalami, in collaboration with the BT-Section (Site C) community of Khayelitsha, Cape Town, and associated local and international partners in Cape Town, South Africa. The project was piloted in 2015. The houses are two stories high and spatially planned with local actor participation and can facilitate alterations in the long term. | https://architizer.com/projects/empower-shack/ |