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# Revolutionizing affordable housing in Africa: A comprehensive technical and sustainability study of 3D-printing technology

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## ABSTRACT

The global challenge of providing affordable and sustainable housing, particularly in Africa's intensified housing crisis, has spurred interest in transformative solutions such as 3D-printing technology. This research addresses a significant gap in understanding the technical and sustainability characteristics of 3D-printed housing, by comprehensively assessing a full-size 3D-printed house. Beyond examining building performance, a thorough life cycle assessment quantifies the whole life cycle carbon and cost, comparing the 3D-printed house with its conventional counterpart. The findings underscore the superior performance of 3D-printed housing in both technical and sustainability aspects. A 48 % reduction in the carbon footprint emphasizes the environmental sustainability of 3D-printed house. Despite a 70 % reduction in construction duration, the initial costs of technology and imported proprietary materials contribute to a higher life cycle cost for the 3D-printed house (381 %) in Africa.

These results affirm the potential of 3D-printing as a sustainable and efficient mechanism for revolutionizing the African housing sector by improving performance and expediting delivery. The study provides valuable insights for housing stakeholders, advocating for the judicious use of 3D-printing and local bio-mediated geomaterials to address African housing crises, enhance residents' quality of life, and, consequently, sustain African cities and society.

## 1. Introduction

Africa faces a persistent and complex housing crisis characterized by a shortage of affordable housing, inadequate living conditions in informal settlements, and a growing urban population. The housing situation in Africa presents a pressing issue characterized by poor quality, slow construction processes, and high wastage, particularly in the low-income housing sector (Mahachi, 2021). Regrettably, a lack of technical knowledge and awareness about innovative construction technologies has hindered the African construction industry's ability to address these challenges effectively (Moghayedi et al., 2022; Windapo et al., 2021). The construction sector has struggled to adopt and leverage innovative technologies to rectify the inefficiencies associated with traditional construction methods, ultimately contributing to the low levels of sustainability and sluggish housing delivery in African countries.

As the demand for more efficient and sustainable housing solutions grows, there is an increasing need to incorporate technological innovation into the design and construction of affordable housing. Despite the potential advantages of 3D-printing technology, its adoption and feasibility within the African context remains largely unexplored, making this study both timely and pertinent. This research aims to investigate the potential of 3D-printing technology for constructing affordable houses in Africa, evaluating its viability as an alternative to conventional construction methods.

The central focus of this study is to assess the technical and sustainability performance of full-size 3D-printed affordable house throughout its life cycle and compare these findings to conventionally

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constructed low-income houses in Africa. This comprehensive research endeavors to shed light on how 3Dprinting technology can address the extensive challenges facing affordable housing and expedite its supply in Africa and similar contexts in the Global South. The study's objectives include:

1. Establish clear technical specifications and performance criteria for 3D-printed affordable house, laying the foundation for a standardized and reliable approach to 3D-printing affordable houses in Africa.
2. Quantify the whole life carbon assessment of 3D-printed affordable house and conduct a comparative analysis with conventional counterparts to assess and understand the environmental implications of both housing construction methods.
3. Calculate the life cycle cost of 3D-printed affordable house and compare it with traditionally constructed dwellings, providing valuable insights into the economic aspects of both approaches and their long-term financial implications.

This research explores uncharted territory within the African context, offering a novel and comprehensive examination of the potential benefits and challenges associated with 3D-printing technology in the affordable housing sector.

The organization of the paper proceeds in the following manner: Section 2 extensively reviews the literature encompassing the global housing crisis and, more specifically, its impact on Africa. This section also delves into an exploration of modern construction methods within the housing sector, providing an overview of 3D-printing technology, particularly in the housing domain. Section 3 serves to contextualize the research, presenting the methodological framework and discussing the methods employed for data collection, analysis, and the overall research protocol. Moving forward, Section 4 meticulously details the results obtained from the building performance and whole life cycle assessment of 3DPC house, offering a comparative analysis with conventional housing characteristics. Section 5 succinctly summarizes and discusses the research findings, aligning them with existing literature. Lastly, in Section 6, pertinent conclusions derived from the research findings are critically discussed, accompanied by appropriate recommendations.

## 2. Literature review

### 2.1. Affordable housing crisis

The global affordable housing backlog and crisis persist as a pressing concern, with nations worldwide struggling to meet the escalating demand for adequate and affordable shelter (Mercader-Moyano et al., 2021). Numerous developed nations are confronting challenges associated with housing affordability. In the United States, the National Low Income Housing Coalition (NLIHC) report reveals that a minimum-wage worker cannot afford a two-bedroom rental home in any U.S. state (Aurand et al., 2023). Skyrocketing housing prices mar the UK's post-pandemic landscape in most cities. In London, the average house price now sits at a staggering more than ten times the average annual salary, forcing countless individuals into precarious living situations (Bricongne et al., 2023). Shared accommodation, unsafe dwellings, and even homelessness are becoming alarmingly common as the dream of owning a home fade ever further from reach for many (Broo et al., 2021).

The housing crisis is particularly pronounced in the Global South and, to a significant extent, in Africa.

The housing crisis in Africa takes on distinctive characteristics shaped by rapid urbanization, population growth, and economic disparities (Moghayedi & Awuzie, 2023). The rapid pace of urbanization in Africa presents a significant challenge in addressing the issue of affordable housing. From a modest 15 % in 1960, the continent's urbanization rate surged to 40 % in 2010 and is anticipated to reach 60 % by 2050. This urban expansion is set to triple the urban populations in Africa over the next 50 years, fundamentally reshaping the region's landscape (UN-Habitat, 2023). The affordability crisis in African housing markets is a pressing concern, particularly for low-income urban households. As the Center for Affordable Housing Finance in Africa (CAHF, 2021) indicates, a staggering 85 % of African nations face a significant challenge (See Fig. 1). A considerable portion of urban households, categorized as low-income, lack the financial means to afford the cheapest newly built houses provided by the private sector, even with the option of mortgage financing arrangements. This underscores the urgent need for comprehensive strategies and interventions to address the affordability gap, ensuring that a larger population has access to decent and affordable housing solutions in the face of rapid urbanization and housing demand.

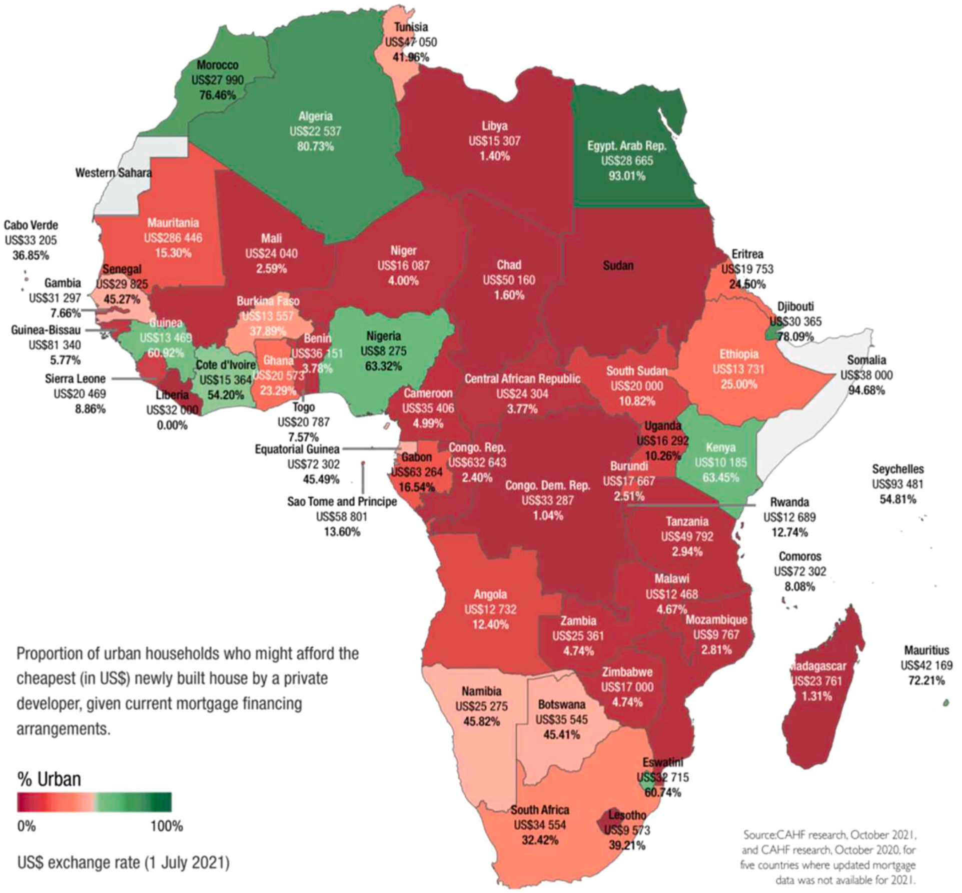
A nation's ability to afford housing is essential to its prosperity because it gives families a place to live, generates jobs, and boosts the economy (Haidar & Bahammam, 2021). This highlights the critical importance of garnering public support and implementing effective policies for affordable housing. Comprehensive strategies and interventions are urgently required to bridge the affordability gap, ensuring that a significant portion of the African population can access decent and affordable housing solutions (Moghayedi et al., 2021). This becomes particularly crucial amidst the challenges posed by rapid urbanization and the escalating demand for housing across the continent.

In Africa, economic challenges compound the affordability issue, leading to a substantial deficit in government-provided affordable housing. The most recent data underscores a staggering shortfall of at least 51 million affordable housing units across the continent (CAHF, 2023). Nigeria bears a considerable burden with a housing deficit of 28 million units, while the Democratic Republic of Congo grapples with an estimated shortage of 3.9 million, requiring the construction of over 260 thousand housing units annually. South Africa faces an affordable housing shortage of approximately 3.7 million units. The gravity of the situation is further emphasized by Statistics South Africa's Household Survey in 2021, which revealed that 12.1 % of the country's 14.75 million households still reside in informal settlements (StatsSA, 2021). The affordable housing deficit in Kenya consists of nearly 2 million houses and continues to grow at a rate of about 200 thousand units a year.

This overwhelming demand for affordable housing and the substantial number of individuals forced to live in substandard conditions, including slums and informal settlements, triggers the urgent need for effective strategies and interventions to address the African housing crisis. The goal is to ensure that every citizen has access to decent and affordable housing, aligning with the constitutional principles of African nations and the aspirations outlined in the African Agenda 2063 (African Union, 2023).

African governments and policymakers are confronted with the formidable challenge of not only managing the unprecedented urban growth on the continent but also ensuring that it translates into sustainable and inclusive development (African Union, 2023). This necessitates strategies that cater for most of their population, particularly those in low-income brackets or below that level. The pressing need for affordable housing solutions becomes increasingly critical as urban populations swell, underscoring the importance of strategic policies to meet the housing demands of this burgeoning urban demographic. African nations support their low-income population and enhance their quality of life, which is directly correlated to the sustainability of cities and society, providing various public housing schemes.

To address the housing crisis, African nations, often with support from international organizations like UN—HABITAT, the World Bank, and the African Development Bank, have implemented various public housing schemes and subsidies aimed at providing affordable housing for their low-income populations. For instance, in South Africa, the government approved the Comprehensive Housing Plan for the Development of Integrated Sustainable Human Settlements under the Breaking New Ground initiative. The primary objective of this plan is to



Source:CAHF research, October 2021, and CAHF research, October 2020, for five countries where updated mortgage data was not available for 2021.

**Fig. 1.** Percent of affordability of cheapest newly built house in Africa (CAHF, 2021).

expedite the elimination of informal settlements across the country while addressing related housing challenges (DHS, 2004). South African Government subsidizes 40 m$^2$ affordable houses using public funds allocated for households with monthly earnings of less than 185 USD.

In Kenya, the Affordable Housing Program strives to offer affordable and quality housing to approximately 17 million citizens in the low-income brackets. This initiative encompasses a range of projects aimed at addressing the housing needs of 31 % of the population (Kieti, 2020). The Family Homes Fund supports affordable housing projects in Nigeria to address the housing deficit, showcasing diverse strategies in African nations. Cross-subsidy housing, implemented in Sudan, Nigeria, Burkina Faso, Zambia, and Ghana, utilizes profits from higher-income developments to subsidize affordable homes. This model generates revenues from upscale developments or loans, creating affordable properties or accessible credit. Public-Private Partnership (PPP), supported by organizations like the African Development Bank, is widely endorsed across Africa. It focuses on collaborative efforts between governmental bodies and the private sector to address the demand for affordable housing and bridge the existing housing gap in Africa (CAHF, 2023).

Despite implementing several national and international affordable housing schemes in Africa, challenges persist in meeting the demand due to financial constraints and slow delivery processes (Mahachi et al., 2022). These challenges are primarily attributed to the lack of digitalization and innovation in planning, design, and construction procedures (Moghayedi et al., 2022). Development costs and project durations in Africa are major contributors to the overall expenses and timelines for affordable housing projects, primarily resulting from the use of conventional materials, methods, and techniques. According to the Center for Affordable Housing Finance (CAHF, 2023), construction costs constitute more than 60 % of the expenses for both low-rise and high-rise low-income housing across the African continent. Despite the relatively low cost of land, which the government often subsidizes, and infrastructure costs covered by the national government, 78 % of the affordable housing project budget is used for construction costs, legal and compliance expenses, and professional and project management fees, as depicted in Fig. 2.

The high construction cost of housing in Africa is primarily attributed to the absence of standardized national designs, necessitating the involvement of numerous professionals in planning, design, and approval processes, which, when combined with the utilization of labor-intensive construction methods, leads to heightened wastages and errors during construction (Windapo et al., 2017). This, in turn, results in expensive and slow delivery of housing projects. Moreover, these prevalent issues in African affordable housing projects significantly impact the quality of these houses, rendering them inefficient in terms of energy and thermal performance. Consequently, these issues collectively impact the quality of life and sustainability of households, African cities, and societies.

While most African nations benefit from robust legislation and regulations governing the technical standards for housing design and construction, challenges persist. For instance, the National Home Building Registration Council's (NHBRC) Home Building Manual (NHBRC, 2015) and the South African National Standards (SANS 10400, 2016) provide essential guidelines and standards that must be adhered to during house construction. However, despite these government interventions and regulatory frameworks, the housing sector still faces difficulties delivering adequate houses, especially to low-income populations (Mahachi et al., 2022). This highlights the pressing need for an innovative approach to housing projects. Recognizing this need, a concerted effort has been made to embrace and promote innovation within the housing

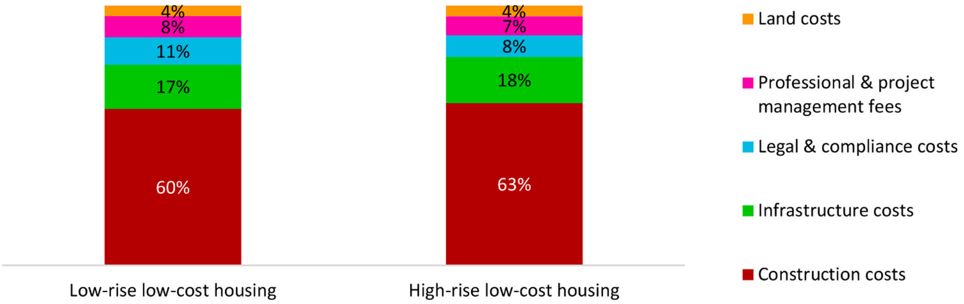


**Fig. 2.** Cost breakdown of different Low-cost housing typologies in Africa (Gardner & Pienaar, 2019).

sector to expedite housing delivery.

Integrating new materials and innovative construction technologies is pivotal in addressing affordable housing issues while concurrently enhancing the quality and efficiency of houses and achieving zero waste, zero-accident, and net-zero carbon housing (Moghayedi & Awuzie, 2023). These advancements mark a paradigm shift toward sustainable and environmentally conscious practices, aligning with global initiatives for climate resilience and reduced ecological impact.

### 2.2. *Innovative building technologies in the housing sector*

In recent years, Africa has experienced a significant upswing in its commitment to innovation within the housing sector, driven by the imperative to address the formidable challenges confronting the construction and housing industries. Several African governments like Kenya, Nigeria, South Africa, and Ghana have pronounced emphasized enhancing housing delivery by leveraging innovation to expedite the process while concurrently improving its quality and efficiency (Mahachi, 2020).

The nomenclature used to describe these innovations often alternates between "Innovative Building Technology" (IBT), “Industrialized building systems” (IBS), and "Modern Methods of Construction" (MMC), signifying a technological renaissance within the construction realm. Regardless of the different terms, these innovations constitute diverse technologies, ranging from pre-manufactured IBTs that involve pre-engineered house or building components, usually manufactured in a factory and assembled or printed on-site, to sustainable materials and cutting-edge digital design tools.

Most African governments have adopted these building standards and policies from developed countries, such as the UK Modern Method of Constructions or US Innovative Building Technologies, regarding innovations in the building and housing sectors. Some African nations like South Africa or Ghana define their policies and standards regarding innovative building materials and systems under the Agrément certificate (Mahachi, 2020).

The burgeoning interest in IBTs across Africa has been motivated by a discerning acknowledgement of the inherent limitations of conventional construction methodologies. The construction industry in some African nations such as Kenya, Ghana, and South Africa have progressively integrated these technologies into their construction industry and particularly housing projects, recognizing their potential to expedite project delivery, streamline operational efficiency, curtail expenses, and augment overall housing cost, time and quality (Tayo et al., 2020).

For instance, The Department of Science and Innovation of South Africa, in its 2021 Science, Technology, and Innovation Indicators, has set a target for IBTs to comprise 60 % of the housing sector’s strategies (DSI, 2021). This move towards innovation represents a promising step in addressing the housing crisis and achieving sustainable housing solutions.

The advantages of IBTs are particularly pronounced when addressing Africa’s affordable housing crisis. These technologies offer a myriad of benefits, including the acceleration of construction schedules, diminished labor demands, heightened energy efficiency, and the capacity to promote sustainable building practices. Furthermore, IBTs promise to stimulate job creation and foster skills development within the construction sector, aligning with broader economic development objectives (Moghayedi et al., 2022).

Notwithstanding their potential, the widespread adoption of IBTs in Africa confronts formidable challenges. Foremost among these challenges is the entrenched resistance to change within the construction industry, which has historically been reliant on conventional methods and materials. Additionally, the initial financial investments required for IBTs implementation may pose constraints for most African stakeholders. Overcoming regulatory hurdles, such as ensuring compliance with building codes and standards, represents another pivotal aspect of facilitating the seamless integration of IBTs into mainstream construction practices of most African countries that mainly focus on conventional materials and methods (Mahachi, 2020)

Within affordable housing, innovation manifests as substituting conventional building products or processes with novel technologies, such as 3D-printing. These technologies cater for a specific set of functions for diverse stakeholders, including occupants, developers, investors, and others involved in the housing production chain. The success of these innovative technologies hinges on their capacity to add value through various means, including heightened functionality, improved performance, and sustainability (Moghayedi et al., 2023). These IBTs may also be deemed successful if they enhance productivity by reducing costs associated with labor, materials, and equipment. Ultimately, these new technologies hold the potential to deliver value by enhancing systemic efficiency, primarily through the compression of construction cycles and operation costs (Olojede et al., 2019). By establishing standardized terminology, African nations are cultivating a forward-thinking approach that accommodates a broad spectrum of construction practices. This inclusive definition encompasses a wide array of IBT methodologies, including pre-manufacturing, on-site innovation technologies such as 3D-printing and robotics, new materials and innovative procedural advancements.

Africa’s journey with IBTs reflects a dynamic landscape of development, adoption, and adaptation, all geared toward addressing critical housing and construction needs. Although challenges persist, the potential of IBTs to revolutionize African construction and housing sectors remains a promising avenue for future growth and development.

### 2.3. *Overview of 3D-printing technology*

Additive manufacturing in construction, commonly known as 3D printing, falls under category 4 in the Modern Methods of Construction (MMC) framework. This category encompasses the remote, site-based, or final workforce-based printing of building parts using various materials based on digital design and manufacturing techniques. The framework further distinguishes it as involving either substantive structural forms or non-structural components (MMC Working Group, 2019).

In 1983, Chuck Hull revolutionized the manufacturing landscape with the invention of stereolithography, a ground-breaking additive manufacturing technique. This innovative process fabricates three-dimensional objects by precisely solidifying resin through a photo-polymerization reaction (Zhang et al., 2019). 3D-printing in construction employs the same fundamental principles but typically utilizes cement-based materials as the primary extrusion material (Tay et al., 2019). 3D-printers typically employ a modified cement-based mixture pushed through a concrete extruder or nozzle under precise three-dimensional control. This extruder is managed by a computerized system, systematically constructing the structure layer by layer. The essential components of this process include a pump, a gantry or robotic system, Computer Aided Design (CAD) and slicing software, and the necessary materials. As a result, the construction process utilizing this technology is largely automated (Lediga & Kruger, 2017). For the success of 3D-printing in construction projects, various aspects will need to be considered such as the type of printer, materials composition, costs and social acceptability, amongst others.

Fig. 3 illustrates the evolution of 3D-printing technology, providing a summarized overview of the developmental history of 3D-printing in the construction industry.

The illustration of the evolution of 3D printing in the construction industry in Fig. 3 underscores that, despite being a relatively recent addition to the construction sector and considered to be in the early stages of technology adoption compared to the manufacturing industry, the concept and application of 3D printing technology have undergone exponential growth within just 30 years. This surge is attributed to the technology's inherent benefits, including a shortened construction period, reduction in labor and material wastage, utilization of topology optimization, high mechanization, non-modeling requirements, facilitation of personalized customization, construction of complex structures, and the creation of uniquely shaped architectural constructions. The industry has swiftly entered a phase of accelerated development,

**Approximations**
1939: William Urschel 3D-prints concrete for a small warehouse in Indiana, USA.
1940: Urschel patents 3D-printed concrete technology for multi-storey structures with integrated reinforcement.
1976: The invention of the inkjet printer lays the groundwork for 3D-printing technologies.

**Setting the Foundations**
1981: Hideo Kodama creates the first 3D-printed scale model building using photo-hardening of plastic polymers.
1984: Charles Hull invents the Stereolithography apparatus (SLA) machine.
1986: Carl Deckard invents Selective Laser Sintering (SLS) technology.
1988: Development of the first SLA 3D-printer.
1989: Scott and Lisa invented Fused Deposition Modeling (FDM).
1990: Commencement of 3D-printing modular building components.

**More Technologies - More Adoption**
1990: Commercializing FDM 3D-printers.
1992: Introduction of SLA 3D-printer to the market.
1993: MIT develops a 3D-printer capable of printing objects made of plastic, ceramic, and metal using CAD software.
1997: First 3D-printed metal process using Laser Additive Manufacturing (LAM).
1997: First feasibility study for 3D-printing in construction was done by Joseph Pegan

**First Architectural Milestones**
2004: Enrico Dini develops D-shape 3D-printer.
2006: MIT creates a large robotic arm for printing concrete and recycled plastic.
2006: Introduction of the first Selective Layer Synthesis (SLS) machine.
2008: First self-replication printer prints most of its components.

**Structural Applications & Large-scale Production**
2011: World's first 3D-printed robotic aircraft and car.
2014: Ten small-scale, cost-effective houses printed with glass fiber and cement in China.
2014: The first commercial 3D concrete printing robot was introduced.
2014: Development of 3D-printing technique for structural steel.
2016: World's first fully functional and permanently occupied 3D-printed concrete office building in Dubai.
2017: First 3D-printed bridge opens in Spain.
2019: The world's largest 3D-printed building was constructed on-site in Dubai.

**Gaining Traction in Housing**
2020: First 3D-printed two-story home enters the German market.
2020: Printing of the largest 3D-printed apartment building in Europe.
2020: First 3D-printed house in Africa, Malawi, using a Gantry printer.
2021: First fully natural 3D-printed construction made of raw earth materials.
2021: Multiple printers synchronized to work simultaneously for 200 hours.
2021: 3D-printed metal bridge emerges in Amsterdam.
2021: World's largest 3D-printed neighborhood comprised of 100 homes in Austin.
2021: First 3D-printed school opens in Malawi.
2021: 3D-printed house in Angola using local materials and concrete.
2022: First 3D-printed house in South Africa using a robotic arm printer.
2023: Introduction of a lightweight insulated wall system using cement-free mineral foam from recycled waste.

**Fig. 3.** 3D-printing evolution in construction industry.

propelled by the numerous advantages offered by 3D-printing in construction.

Moreover, the evolution and development of 3D-printing in the construction industry exhibit several noteworthy characteristics: (1) The industry is witnessing continuous growth in the number, scale, and geographical locations of actual 3D-printing projects; (2) Continuous emergence of novel materials and novel technologies with a focus on cost, efficiency and environmental considerations; (3) Constant evolution of new engineering applications with seamless integration into other technologies; (4) Predominant focus on addressing the global housing crisis through various 3D-printing applications.

### *2.4. 3D-printing in housing sector*

3D-printing offers a multitude of advantages when applied to the housing sector. Once optimized, a 3D-printer can reduce 30 % to 60 % of construction waste compared to traditional construction methods due to its precise nature (Zhang et al., 2019). Moreover, the automated process of 3D-printing reduces on-site labor requirements and, consequently, labor costs, which typically constitute more than half of the expenses in conventional housing projects, by 50 % to 80 % (Zhang et al., 2018). Additionally, the system's design flexibility eliminates the need for formwork, reducing both the duration and cost of projects, particularly those housing involving concrete structures. The cost of formwork typically constitutes 35 %–60 % of the overall costs of concrete structures (Ma et al., 2018). This elimination allows for customized structural elements, further reducing housing construction costs. Kreiger et al. (2019) study demonstrated that 3D-printed construction is 10–25 % more cost-effective than building with concrete masonry units and 25–37 % cheaper than cast-in-place construction, primarily due to the elimination of formwork costs.

3D-printing substantially enhances architectural adaptability, construction flexibility, and buildability (Mahachi, 2021). This advancement can lead to a remarkable reduction in design time, potentially up to 60 %, while embracing lean construction principles (Wu et al., 2018). These principles involve the standardization of tasks and continuous process improvement to streamline the construction process and eliminate inefficiencies. The architectural adaptability and buildability of this technology not only contribute to cost savings but also facilitate rapid design and prototyping of housing, directly resulting in shortened housing delivery timelines by 55 % (Tay et al., 2017).

Life Cycle Assessment (LCA) offers insights into the environmental advantages and challenges associated with 3DPC in housing construction. While 3D-printing offers significant benefits in terms of reduced labor and formwork costs, waste minimization, accelerated production timelines, and increased flexibility and adaptability in both design and construction phases, it is crucial to acknowledge its impact on carbon emissions. The use of 1.5–2 times more Portland cement in 3DPC compared to conventional casting significantly increases the carbon embodied in materials, contributing to approximately 20 % of the life carbon emissions of a house (Han et al., 2021; Sanjayan et al., 2018). Scholarly studies have explored strategies to mitigate the carbon footprint of 3D-printing materials. Incorporating green and recycled aggregates in 3DPC has shown a marginal effect on life carbon emissions, contributing to approximately 2 % of the total global warming potential when fully replacing virgin aggregate with recycled concrete aggregate (Han et al., 2021). In efforts to enhance sustainability, researchers have investigated alternative materials and mixtures. A study by Mohammad et al. (2020) suggests that optimizing 3D-printing concrete mixtures with fly ash and nanofibers can reduce the carbon footprint by over 70 %. Additionally, substituting conventional Portland Cement with geopolymers has demonstrated an 80 % reduction in greenhouse gas emissions compared to traditional cement manufacturing (Bazli et al., 2023).

Research examining the energy demand and carbon emissions during the 3D-printing construction process indicates that 3D-printer operations account for only 2 % of the overall life cycle emissions of 3DPC houses (De Schutter et al., 2018). Notably, this electricity is often supplied from green and renewable sources, making it a more environmentally friendly option. This stands in contrast to the carbon emissions associated with the construction of conventional housing, which constitute 2–5 % of the house's overall life cycle emissions, primarily originating from fossil fuel sources (Moghayedi et al., 2023).

In the absence of a comprehensive whole-life cycle assessment for an actual 3D-printed house, researchers have estimated that 3D-printed houses could potentially decrease the environmental impact of housing projects by up to 50 %, primarily due to the significantly lower cumulative energy demand involved in manufacturing products through 3D-printing, ranging from 41 % to 64 % less than conventional methods (Gebler et al., 2014).

While there are significant reductions in labor, equipment, scaffolding, and formwork costs for 3D-printed houses and an average 40 % reduction in material waste, the material cost for 3D-printing is higher than conventional and local materials. This is mainly because the current 3D-printing materials are either produced in laboratories or exclusively manufactured by some 3D-printing companies, considering them as proprietary materials. The high cost of 3D-printing materials results in the construction cost of 3D-printing being higher than conventional housing projects. For instance, Nodehi et al. (2022) reported an 80 % increase in average cementitious 3D-printing materials, and De Schutter et al. (2018) recorded a 70 % increase in 3D-printing concrete materials cost due to the high-strength and fine-grained concrete mixture used in 3D-printers.

The absence of a comprehensive LCC hinders the accurate estimation of the overall cost of 3D-printed houses compared to conventional methods. However, the prevailing consensus among scholars suggests that the current cost of 3D-printed houses is expected to be higher than that of conventional houses, especially in the context of low-income and subsidized housing (Mahachi, 2021)

A study by Ma et al. (2018) that analyzed economies of scale and breakeven for 3D-printing technology in the construction industry explored the relationship between the number of units, complexity, and cost of units for both conventional and 3D-printed projects. Their analysis revealed that the cost of 3D-printing remains relatively uniform for each unit of production, minimally impacted by the total number and complexity. In contrast, conventional projects experience a decrease in cost for each incremental unit of production with the total number of construction objects, while the cost per unit increases with complexity. Therefore, 3D-printing demonstrates superiority in low-to-medium-sized construction projects and relatively complex projects like mass housing projects.

3D-printing, like other technologies, has its own drawbacks, despite its numerous economic, social, and environmental advantages and benefits. Overall, the main drawback of 3D-printing systems is the high initial capital outlay, which can be a significant barrier to adoption, particularly for affordable housing projects where cost efficiency is crucial (Bazli et al., 2023).

However, as technology adoption rates and throughput of 3D-printing improve in the years to come, costs are expected to decline gradually in construction projects. This reduction in 3D-printing costs, driven by technological advancements and increased adoption, will be accelerated by the rapid development of bio-mediated geomaterials for 3D-printing in construction. The overall technical, economic, environmental, and social advantages and drawbacks of 3D-printing in housing projects are concisely summarized in Table 1.

According to Ma et al. (2022), which focused on technology readiness and 3D-printing developments, most applications for 3D-printing technology are in the housing sector. However, elements such as bridges and street furniture housing have been more widely targeted using 3D-printing, as shown in Fig. 4. Over the years, the industry has experienced significant growth, with companies and organizations from around the globe actively engaging in the advancement of this

**Table 1**

Advantages and drawbacks of 3D-printing in the housing sector.

| Aspect | Advantages | Drawbacks |
|---|---|---|
| Technical | ✓ Improve flexibility, adaptability, and overall buildability.<br>✓ Faster design and construction time (60 %–90 %).<br>✓ High level of design freedom for intricate and complex structures.<br>✓ Mass production and mass customization enable personalized designs on a large scale.<br>✓ Element human errors and deficits are reduced.<br>✓ High precision and structural integrity in the final product.<br>✓ Allows construction in hard-to-reach or hazardous locations. | × Require minimum training and digital competency.<br>× Limited material choices and reliance on proprietary materials.<br>× Lack of local building codes and regulations regarding new materials, 3D-printing processes, and inspection.<br>× Not able to print entire structures/projects.<br>× Restrictions on the size of printed structures.<br>× Some 3D-printing materials may not match the strength of traditional construction materials. |
| Economics | ✓ Reduce labor costs (50 %–80 %).<br>✓ Eliminate formwork costs (35 %–60 % of overall costs of concrete structures).<br>✓ Reduce material wastage (40 %).<br>✓ Eliminate human errors and rework due to defects.<br>✓ Reduce construction costs through mass production.<br>✓ Reduce transportation by minimizing the need for transportation of large, prefabricated components. | × Higher material costs for proprietary or lab-produced materials (50 %–80 %).<br>× High initial investment costs.<br>× Higher upfront costs and materials impact the feasibility and affordability of small projects. |
| Environmental | ✓ Reduce carbon emissions during the construction stage.<br>✓ Reduce carbon embodied using bio-based local materials.<br>✓ Reduce carbon emissions during the operation stage due to better building performance.<br>✓ Potential for using green and recycled building materials.<br>✓ Use clean electricity from renewable sources during printing (eliminate fossil fuel).<br>✓ Reduce carbon emissions due to less transportation of large components and equipment. | × Increase the carbon embodied in cementitious materials (20 %) |
| Social | ✓ Enhance quality and improve the quality of life for users/residents.<br>✓ Opportunities for local employment with short training.<br>✓ More safe and sustainable jobs off-site and on-site.<br>✓ Upskilling and reskilling unskilled and semi-skilled construction workers. | × Reduce low-skill jobs.<br>× Limit the number of jobs directly created in the community.<br>× Low end-user acceptance due to rough finishes. |

technology.

In 2014, Win Sun showcased the potential of 3D-printed construction by printing ten houses (200 $m^2$) in a day using high-grade cement and glass fiber (Puzatova et al., 2022). Subsequently, in 2015, an Urban Cabin was 3D-printed in Amsterdam, demonstrating the use of bio-plastic materials for housing solutions. In 2018, ICON secured a building permit to construct a 74.32 $m^2$ house within 24 h for $10,000, solidifying 3D-printing as a promise for affordable housing (Valente et al., 2019). In 2021, Mario Cucinella Architects and WASP crafted a low-carbon housing prototype entirely through 3D-printing, using clay as the primary material. This 60 $m^2$ dwelling draws inspiration from vernacular architecture and sustainable building techniques (Leschok et al., 2023).

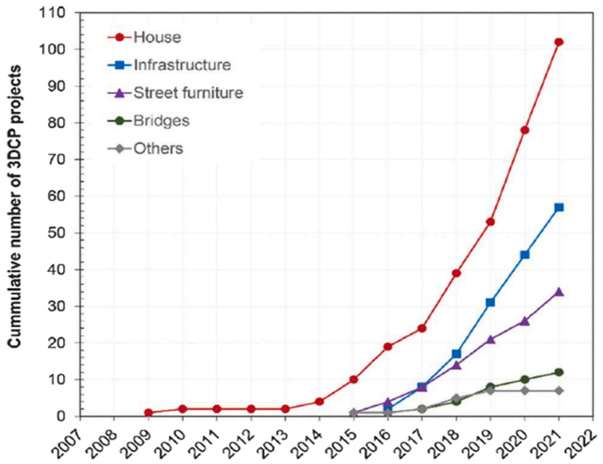


**Fig. 4.** Overview of 3D-printing applications (Ma et al., 2022).

Another notable project in Europe achieved load-bearing walls through 3D-printing technology, gaining commercial approval in 2021. Tenants were paid rent for residing in the pioneering 94 $m^2$ 3D-printed home. In 2022, ICON introduced the Vulcan construction system, set to 3D-print an entire neighborhood with homes spanning up to 279 $m^2$, meeting International Building Code standards. South Africa witnessed the construction of its first 40 $m^2$ 3D-printed house in 2023, designed following the standard subsidized housing blueprint, aiming to assess the technology's strengths and weaknesses in addressing housing challenges (Christen et al., 2023).

As listed in the examples of 3D-printing in housing sectors above, numerous projects have launched 3D-printing initiatives for housing, collectively driving the advancement and proliferation of this revolutionary technology, especially in developed countries. However, the potential benefits and possible repercussions of 3D-printing for developing countries, which are grappling with a myriad of socioeconomic challenges, remain underexplored and warrant further comprehensive evaluation and study.

## 3. Methodology

The study aims to investigate the sustainability of 3DPC houses as potential IBT for mass customization and mass production of affordable housing to address Africa's shortage of adequate housing. To this purpose, parametric technical and mechanical specifications, life cycle assessment, and building performance were considered and compared to a similar conventional low-income house to evaluate the impact of the 3D-printing method on the sustainability of affordable houses.

In this case study, only the superstructure (walling) of the low-income house was 3D-printed. The foundation and roofing system were constructed using conventional methods. As a result, the analysis and findings are confined to the 3D-printed walling systems.

The study adhered to a quantitative positivist approach to achieve robust and quantifiable results, specifically adopting a true experimental design. This methodological choice prioritizes objective measurement and empirical evidence, aligning with the study's aim to systematically assess the impact of 3D-printing methods on sustainability. The structured nature of true-experimental designs allows for the establishment of cause-and-effect relationships, promoting the generalizability and replicability of findings (Gribbons & Herman, 2019). Controlling extraneous variables enhances the reliability and validity of the study's quantitative data, facilitating various quantitative analyses to identify patterns and trends (Bloomfield & Fisher, 2019).

The rationale for selecting this methodology stems from the study's specific objectives. The true-experimental design is well-suited for exploring causation, which is crucial in understanding the relationship between 3D-printing methods and the sustainability of affordable housing. Moreover, the quantitative positivist approach is apt for the study's focus on quantifiable sustainability metrics, such as LCA and building performance. This methodology enables a systematic and numerical comparison between 3D-printed houses and traditional construction, supporting the study's aim to generate actionable insights for data-driven decision-making in addressing the global shortage of affordable housing. Overall, the chosen methodology enhances the methodological rigor of the research, ensuring a structured and controlled investigation into the sustainability dimensions of 3D-printed affordable housing.

The research methodology unfolded in a systematic progression through four key steps, each meticulously designed to contribute valuable insights into the sustainability dimensions of 3D-printed affordable housing.

Step 1: Adopt a common low-income house design and generate electronic drawings and a 3D model using Computer-Aided Design (CAD) software.

Step 2: Develop a 3D-printing plan, including printing segmentation and sequencing, materials specifications, and formulating the concrete.

Step 3: 3D-print the low-income house and integrate steel reinforcement and building services.

Step 4: Conduct a comprehensive building performance, including thermal, humidity, airtightness observations, and whole life cycle assessment of the 3DCP, and cross-compare it with similar conventional low-cost housing.

The detailed research protocol adopted for this study is presented in Fig. 5 below.

### 3.1. Life cycle assessment

The Life Cycle Assessment (LCA) is a robust methodology for evaluating the environmental performance and cost of products and services, making it an essential tool for assessing buildings and their materials (Bjørn et al., 2020). This study strictly follows the terminology and division of life cycle phases as outlined in EN15978, which establishes criteria for evaluating the environmental impact of buildings (BSI,

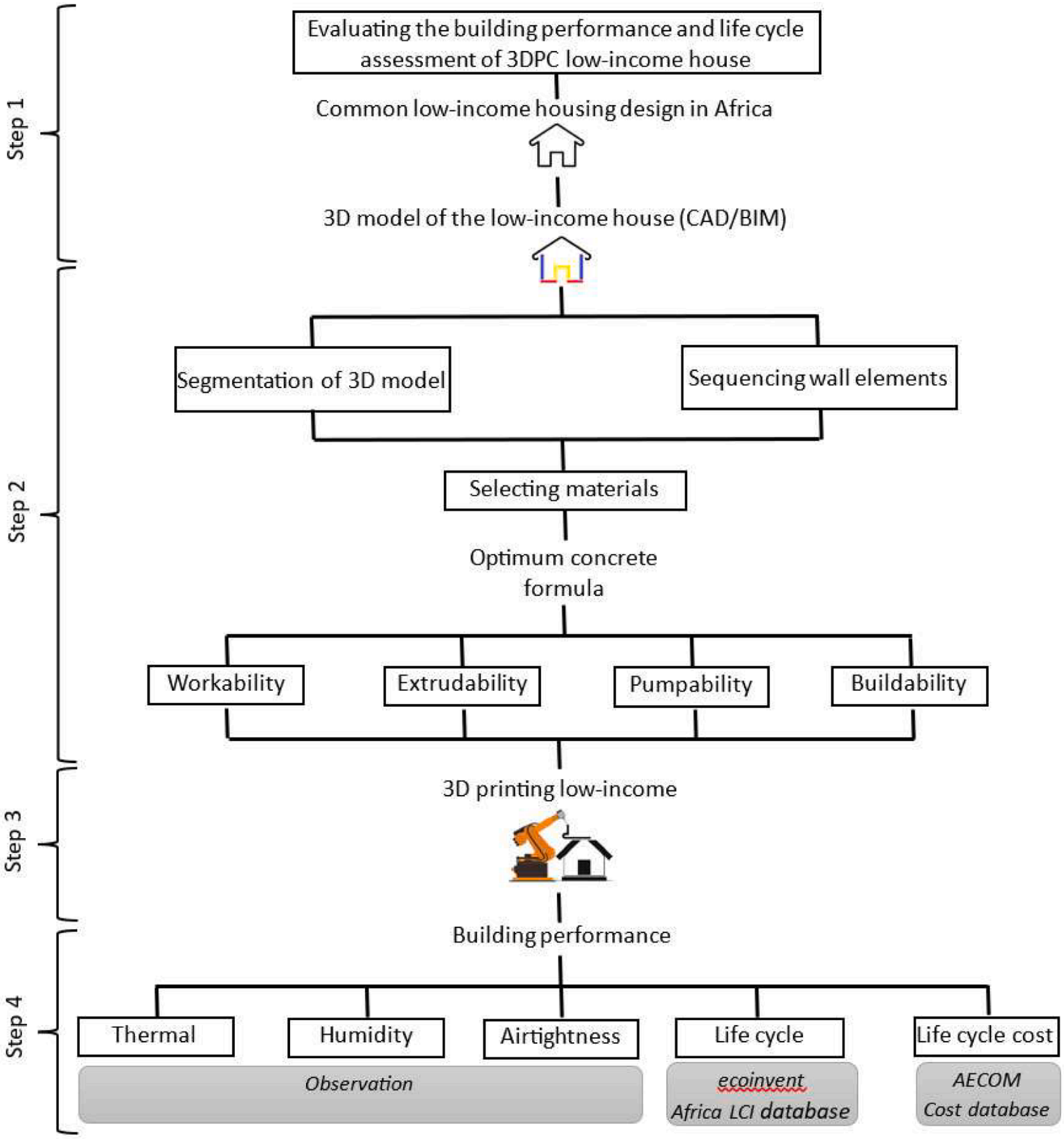


**Fig. 5.** Research protocol.

2011).

Moreover, the research closely aligns with the overarching principles outlined in ISO14044 for Life Cycle Assessment (LCA) and Whole Life Carbon Assessment (WLCA) RICS guidelines. This alignment encompasses four key aspects of LCA: 1) goal and scope, 2) Inventory analysis (LCI), 3) Impact assessment (LCIA), and 4) interpretation (ISO, 2006). Consequently, the terminology used in this study adheres to the cradle-to-cradle WLCA framework established by EN 15,804 (product level) and EN 15,978 (building level), as depicted in Fig. 6.

### 3.1.1. *Goal & scope definition*

This WLCA aims to measure and compare the environmental impact of 3DPC as a potential solution to address the housing crisis in Africa against a conventional low-income house. The evaluation of global warming potential (GWP) encompasses emissions at five stages: production (A1–3), construction (A4–5), use (B1–6), end-of-life (C1–4), and beyond building life cycle (D), following a cradle-to-cradle approach according to EN 15,978, as depicted in Fig. 6. This study's Functional Unit (FU) is 1 $m^2$ of gross internal area (GIA) in a house intended for a 50-year lifespan, accommodating a family of four. The analysis focuses on a standard one-story detached low-income fully subsidized house with a floor plan of 40 $m^2$ and a total net wall area of 90 $m^2$, excluding door and window openings, as shown in Fig. 7.

### 3.1.2. *Inventory analysis*

The life cycle inventory (LCI) involves compiling all materials used to construct the building and forming the FU for 3DPC and a conventional house designed to last 50 years. The LCI should specify each component's quantity and total mass, allowing the calculation of the percentage of the overall product weight.

In accordance with ISO 14040 guidelines, elements constituting less than 1 % of the overall weight have minimal influence on the analysis and may be excluded (ISO, 2006). Therefore, internal finishings and building services, such as mechanical, electrical, and plumbing, were disregarded in both cases. Since the 3D-printer only printed the superstructure (walls) of the house, the cradle-to-cradle assessment was limited to the superstructure of two houses. Due to their similarity, the sub-structure and roof were excluded from the analysis.

For a transparent and comprehensive analysis, the following assumptions were considered:

- Material waste factors during production, transportation, and construction are included in the required materials during the production stage and in the weight of materials in the FU.
- Emissions related to materials wastage on-site are accounted for in the production stage (A1–3), and emissions from construction and installation activities (A5) are computed following AECOM guidelines (2023).
- In the in-use phase (B1–5) of both the 3DPC and conventional house, it is assumed that the superstructure of both houses will require minimum use and maintenance 10 % (B1–2). Due to the high durability of concrete and bricks, no repair (B3), refurbishment (B2), or replacement (B5) is anticipated over the lifespan, following RICS recommendations (2017).
- At the end of the building's service life for the conventional system, recycling (D) is envisioned for 20 % of bricks from walls, while the remaining 80 % is demolished and transported to the landfill (C1–4), as recommended by RICS (2017). For 3DPC, it is anticipated that 100 % of reinforcement and 3D-printed concrete will be recycled (D), as the 3D-printing material supplier instructed.
- For end-of-life scenarios, both landfilling and recycling transport distances (C2 and D) were set at 50 km.

The substructures of both houses consist of surface beds with thickened edge beams (raft foundation), constructed using reinforced concrete and designed according to SANS 10,400 (SABSA, 2011). The superstructure of a conventional low-income house comprises loadbearing brick walls with a thickness of 200 mm. Internal partitions consist of 100 mm thick bricks coated with plaster on both sides, following SANS 10400 (2011). The 3DPC utilizes minimal reinforcement for columns and 140 mm thick cavity walls for internal and external walls using proprietary fine concrete. Both houses use timber roof truss coverings, corrugated steel sheets, and insulated gypsum board ceilings for roofing systems.

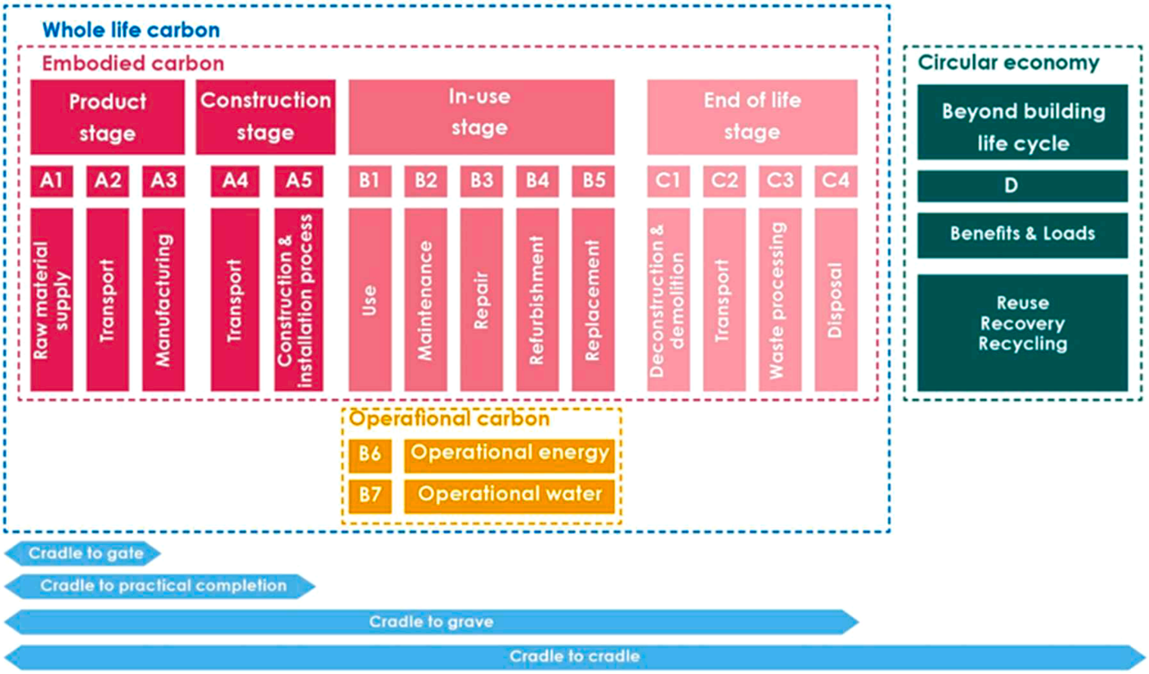


**Fig. 6.** Life cycle stages of a building (BSI, 2011).

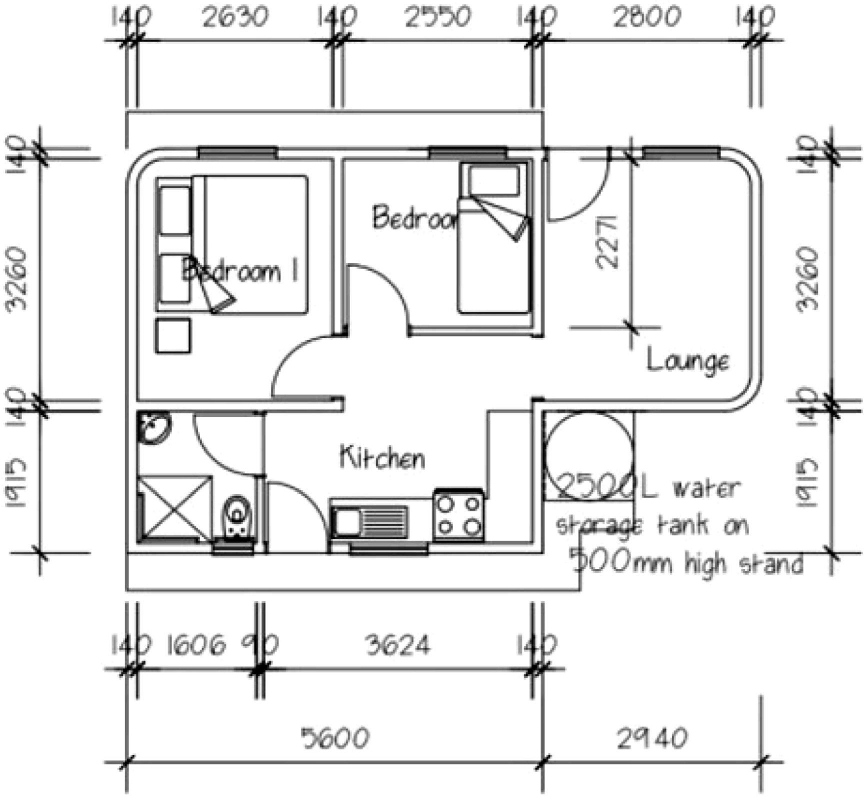


**Fig. 7.** The layout of a common low-income house for printing purposes.
Note: Gross floor area: 40 $m^2$, Gross internal area: 36.03 $m^2$, Foundation: Raft, Roof: steel sheet on wooden trusses. The wall height is 2.4 m, the total wall area of 92 $m^2$

### 3.1.3. *Impact assessment*

The life cycle impact assessment (LCIA) involves examining both embodied and operational effects, providing a comprehensive view of the life cycle consequences of a product or system. This assessment spans the entire life cycle, from cradle to cradle (A-D in Fig. 6), and employs the IPCC GWP 100a impact assessment methodology, as detailed in Section 3.1.1. During the assessment phase, SimaPro 9.2 software, in conjunction with the ecoinvent v3 database Global, is utilized. Given the absence of 3D-printed concrete material in the ecoinvent database, Environmental Product Declarations (EPDs) for this material are used.

The thermal performance evaluation of the conventional system follows the standards set by SANS 10,400, while observations on-site are utilized to assess the thermal performance of the 3DPC. To determine the annual energy usage for the houses (B6), EDGE software is employed for modeling, and the results are quantified in kWh/year.

In both scenarios, all regulated energy is supplied by electricity, except for the cooking stove, which uses LPG. The electricity for both houses is sourced from the national grid, with a carbon dioxide equivalent intensity of 1.06 kgCO2e/kWh (Eskom, 2021) considered in the life cycle impact assessment (LCIA).

## 4. Results

The results of the experimental project have been organized and presented in this section based on the five steps of the methodology. Each step's findings have been classified and outlined to provide a clear and comprehensive understanding of the outcomes.

### 4.1. *Design of affordable house*

The affordable 3D-printed house was specifically designed for subtropical highlands with dry winter climate zone environmental conditions in South Africa. The location of the project is in Johannesburg city, where the temperature ranges between 15 and 33 °C in summer and 4–20 °C in winter.

A typical 40 $m^2$ low-income house planned as a prototype case study input for evaluating the sustainability performance of a 3D-printed affordable house was adapted to print (See Fig. 7). The study does not center solely on the case study design; rather, it employs it as input to assess how the 3D-printing method affects a house's performance throughout its lifespan, which, in this case, is regarded as 50 years. To test the flexibility and buildability of the 3D-printing method, three sharp corners of the house were modified to curve, as shown in Fig. 7.

The electronic drawings and a 3D model of a modified affordable house were produced in CAD using Rhinoceros 3D computer graphics software. Chysel software was used to slice the drawings, which were then converted to .sys files in a 3D-printable format.

The automated 3D-printing design process holds the potential to substantially streamline the design phase of large-scale housing projects, leading to significant time savings during the mass production of low-income housing. This is also highlighted by research conducted by Bello & Memari (2023), who undertook comprehensive research that reviewed concrete printing projects by several companies across the world.

### 4.2. *3D model of a house for printing affordable house*

The Cybe robotic crawler was employed, comprising two primary components: a mixing pump station and a robotic arm station equipped with a crawler system, as depicted in Fig. 8. This system offers an estimated build volume of 3 × 3 × 4.5 m and operates on 7 axes, achieving a print speed ranging from 50 to 600 mm/s.

The first phase of the 3D-printing planning process was producing segmentation and sequencing of the structure. Segmentation is the

**Fig. 8.** Robotic arm 3D-printing system.

process where the structure is divided into various structural elements primarily based on the robotic arm's reach and the space requirement to accommodate the system's movement. Based on the maximum robotic arm reach of 3.2 m and the spatial layout, the structure was divided into 13 wall elements, as shown in Fig. 9.

Sequencing is identifying a logical printing sequence of the structural elements that will allow the robot to avoid being trapped inside the structure during printing.

The subsequent step in 3D-printing planning involved establishing precise reference points. The robotic arm's positioning is paramount in relation to the wall being printed. These reference points play a crucial role in determining the placement of the robot's legs relative to the structural elements that will be printed. For each wall element, a total of 7 reference points were used, with three designated for the printer legs and four for the edges of the wall element.

This research project employed proprietary material to meet all the essential properties required for 3DPC. This ensured that the material possessed favorable attributes in terms of workability, pumpability, extrudability, and buildability. The key characteristics of the proprietary material used are detailed in Table 2 for reference.

Enhancing the performance of 3D-printing relies heavily on the choice of materials, ensuring attributes such as workability, open-time, extrudability, and buildability meet standards. The corresponding laboratory results for the material utilized in 3DPC are outlined in Table 3:

### 4.3. *Print the affordable house*

After completing steps 1 and 2, the construction phase of the 3D-printed house commenced. Before laying the foundation, the area was cleared, cleaned, and compacted using traditional methods. The primary factors that influenced the foundation design in this case study were the machine loads and the size of the structure. This load is distributed among the three legs. The foot of one leg is 400 mm in diameter and carries a load of 42 kN.

The 3D-printing process for walls started by ensuring that the material viscosity was below 2.2 ps.s to meet workability, extrudability, and pumpability requirements. Once the material reached the right

**Table 2**
3DCP Proprietary material characteristics (Cybe, 2020).

| Item | | Measurement |
|---|---|---|
| Grain size | | 0–3 mm |
| Setting time | | 3–5 min |
| Compressive strength | 5 h | 20 MPa |
| | 1 day | 25 MPa |
| | 7 days | 30 MPa |
| | 28 days | 40 MPa |
| Flexural strength | 5 days | 4 MPa |
| | 7 days | 5 MPa |
| | 28 days | 6 MPa |
| Density | | 2100–2200 kg/m$^3$ |
| Flow | | 130 mm |
| Depth of water penetration | | 23 mm |
| PH Value | | 12 |

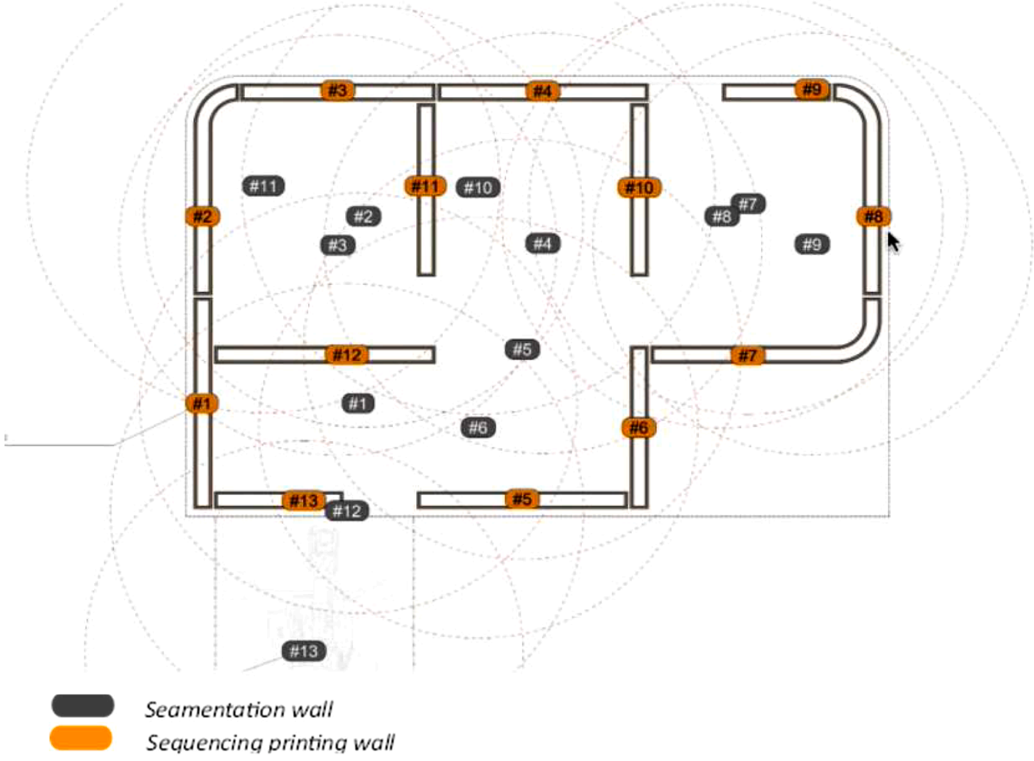


**Fig. 9.** Segmentation and sequencing of walling in case study.

**Table 3**
3DPC material specifications and performance.

| Specification | | Performance |
|---|---|---|
| Workability | Flow behavior of fresh materials within the pumping system | 155 mm |
| Open-time | Printability time for the wet mixture | 300 s |
| Extrudability | The capacity of mixture to form a continuous and intact filament through the printer's nozzle | 3.8 pa/s |
| Buildability | Printed material's resistance to deformation under load | 3000 mm |

viscosity, the printing of the wall elements commenced, eliminating the need for any prior material discard. This study used 50 bags of 25 kg material for the 3 × 2.5 × 0.23 m wall element. Due to a lack of experience among the operators, there was an initial wastage of 20 %. However, enhancing the operators' experience reduced this wastage gradually to 8 %.

The material wastage level in the process of 3D-Printing walls in this case study is significantly lower than the average wastage of materials in conventional African housing projects, as reported by Fitchett and Rambuwani (2022), where it stands at 35 %. This is further corroborated by a 37 m$^2$ house built by Strommen in 2022, which reported that 70 % less concrete could be used by placing materials only where needed. This decrease in material wastage within the 3D-printing system has been consistently observed and documented by Tu et al. (2023) research on recent advancements and future trends in 3D-printing concrete.

The uninterrupted print duration for each wall was approximately 50 min. Cumulatively, including calibration and setting-out, the total time per wall element was 70 min. However, the printing time for wall elements was reduced by 30 % as operators and workforces gained experience and familiarity with the setting-out, calibration of the robotic arm station, and the 3D-printing of walls.

### 4.3.1. *Incorporating reinforcement and services*

Incorporating steel reinforcement and building services into the 3D-printing process for the walls was achieved by utilizing the cavity spaces within the walls. This approach facilitated the integration and circumvented any constraints during the set-up and actual printing of the walls.

Once the foundations were laid, the exact locations of the columns were marked to allow for the integration of reinforced columns. Holes were drilled in the foundation to insert the starter bars, followed by the printing of the formwork around the steel.

To avoid any hindrance to the 3D-printer while integrating vertical rebars in column areas, the vertical column reinforcements were cut at a length of 1.2 m. This specific length of steel reinforcement allowed the 3D-printer to freely print concrete around the reinforcement freely, ensuring a robust connection between the two materials while minimizing the need for excessive cutting and overlapping (only 2 overlaps were required), as depicted in Fig. 10. Consequently, the 3D-printed structure acted as concrete molds around the reinforcement, filling the columns with concrete. This approach enhanced the overall structural integrity of the printed structure and ensured a strong bonding between the concrete and steel elements.

Similarly, the cavities within the walls were designed to function as conduits for the passage of mechanical, electrical, and plumbing services, as illustrated in Fig. 11.

### 4.3.2. *Workforce???*

The 3D-printing process relies on a coordinated workforce, encompassing unskilled, semi-skilled, and skilled labor. During the 3D-printing of the house, the workforce encompassed various roles, as outlined in Table 4.

The entire process of 3D-Printing the walls of the affordable house was completed within an 8-hour timeframe, and the final 3D-Printed affordable house is depicted in Fig. 12.

Considering the workforce data above, the workforce requirements for 3D-printing the walls of an affordable housing unit are significantly lower than those for conventional construction methods. Meanwhile, 3D-printing requires 3 skilled laborers and 2 semi-skilled laborers for a single day's duration, totaling 40 man-hours. The conventional system requires 2 skilled, 2 semi-skilled, and 2 unskilled employees over 3 days (AECOM, 2023), equating to 144 man-hours.

This comparison clearly demonstrates the substantial advantages of the 3D-printing system. It eliminates the need for unskilled labor in 3D-printing projects while increasing the demand for highly skilled labor. This finding proves the social sustainability of this automation in housing projects by reskilling and upskilling laborers (Mahachi, 2021). Ultimately, 3D-printing results in a remarkable reduction in man-hours of constructing affordable houses by 72 %. These findings align harmoniously with research conducted by Ahmed (2023), who investigated the economic benefits of 3DPC.

## 4.4. *Performance evaluation and life cycle assessment*

After printing the walls of the affordable house, the real data was used to evaluate the building performance and sustainability of the

**Fig. 10.** Integrating steel reinforcement to 3DPC house.

**Fig 11.** Cavities layout to incorporate services.

**Table 4**
Workforce for 3DPC house.

| Workstation | Labor | Skills and Responsibilities |
|---|---|---|
| Mixing Pump Station | Semi-skilled<br>Skilled | Stack cement bags next to MPS station to ensure a continuous supply of materials.<br>Adjust water pressure and admixtures to maintain the correct consistency of the material during the printing process. |
| Robotic Arm Station | Skilled | Proficient in CAD and slicing software to translate designs into G-code.<br>Interpret G-code to monitor printing progress.<br>Continuously monitor the nozzle's activity for precise adherence to the printing path.<br>Adjust print speed.<br>Execute emergency stops if needed. |
| Support Works | Skilled<br>Semi-skilled | Install steel reinforcement.<br>Work on building services.<br>Provide support for openings in the structure. |

3DPC house and compare it with similar conventional houses as a baseline.

### 4.4.1. *Thermal, humidity and airtightness*

The actual performance of the 3DPC house and Conventional house, which encompasses variations in temperature between winter nights and summer days, as well as the humidity levels during winter, were monitored. The findings from these observations have been consolidated and are presented in Table 5.

As indicated in Table 5, the 3DPC house demonstrates a slightly improved temperature performance in comparison to the conventional house during both winter nights (2 °C outside, 15 °C inside) and summer days (33 °C outside, 22 °C inside). This slight temperature advantage in the 3DPC house can be attributed to the presence of a cavity in the structural 3DPC wall, combined with the absence of thermal insulation in both the baseline and the 3DPC houses. Nonetheless, the winter temperature performance of the 3DPC house falls below the recommended 18 °C desirable standards set by the South African building code, emphasizing the necessity of incorporating insulation within the cavity spaces of the 3DPC walls. Similarly, cavities in the 3D-printed walls contribute to the lower humidity levels in the 3DPC house during winter compared to the baseline, as shown in Table 5.

**Table 5**
Thermal and humidity performance.

| Description | Conventional house | 3DPC house | Improvement |
|---|---|---|---|
| Temperatures difference on winter night | 8 °C | 13 °C | 5 °C |
| Temperature difference on summer day | 7 °C | 11 °C | 4 °C |
| Level of humidity in winter | 45 % | 32 % | 13 % |

**Fig 12.** 3D-printed affordable house.

The superior thermal and humidity performance of 3DPC houses compared to conventional houses has been documented and corroborated by researchers who investigated various materials as well as the print geometry (Marais et al., 2021).

Moreover, the airtightness of the 3DPC house was evaluated using a FLIR TG267 infrared camera (with an accuracy of ±1.5 °C) on a summer day when the outside temperature was 33 °C. The infrared thermograms of individual wall elements and the connections between two adjacent wall elements of the 3DPC house are depicted in Fig. 13.

The infrared images clearly demonstrate uniform temperature distribution across the wall layers (Fig. 13), indicating the absence of thermal bridges within the same wall layers. This uniformity is primarily attributed to the strong adhesion between printed layers, achieved through meticulous selection of concrete formula, slump, and printing speed, tailored to the site's temperature, as well as precise printing segmentation and sequencing. Additional 3DPC factors, such as the number of layers per printing, rest time during the process, and layer-by-layer appearance, further contribute to the favorable airtightness of the 3DPC wall layers. A better air tightness of 3DPC walls compared to bricks and mortar walls has also been noted by Sun et al., Li and Feng (2021).

However, it is essential to note that an infrared thermogram reveals the presence of a thermal bridge between two 3D-printed wall elements, as indicated in Fig. 13. These thermal bridges significantly impact the airtightness of the 3D house and are the primary cause of its suboptimal thermal performance. To rectify this issue and enhance airtightness, employing standard insulation tape to bridge and seal the gap between these wall elements is crucial. The incorporation of insulation tape serves not only to eliminate thermal bridges but also to improve airtightness, thermal efficiency, water insulation, and structural integrity in 3DPC. This enhancement will contribute substantially to overall energy efficiency and building comfort, making it a more sustainable and effective solution for affordable housing.

#### 4.4.2. Life cycle assessment

The life cycle assessment involved calculating the WLCA and LCC for the 3D-printed house in a 50-year life span, juxtaposing them with those of a standard low-income house constructed with traditional bricks and mortar in Africa.

*4.4.2.1. Whole life carbon assessment (WLCA).* The assessment of WLCA for both 3DPC and conventional houses utilized the ISO 14,040 methodology and the EN 15,804 framework, as discussed in Section 3.1. As shown in Table 6, the carbon emissions for the FU of both houses' walling systems were assessed across five stages: production, construction, in-use, end-of-life, and beyond-life. This analysis was conducted through SimaPro software, utilizing the ecoinvent and Cybe EPD. A heat map is utilized in Table 6, employing a color scale, to readily pinpoint building stages associated with high levels of carbon emissions.

As shown in Table 6, the WLCA of 3DPC house are significantly lower than conventional house (−48 %). This reduction in WLCA is mainly attributed to three factors. Firstly, during the production process, there is a 25 % decrease in carbon emissions due to the use of a large amount of recycled materials in the proprietary materials used for printing. These materials emit up to 60 % less CO2 than traditional Portland cement (Cybe, 2020). Secondly, during the use phase, there is a 42 % reduction in carbon emissions because of the higher durability of 3DPC walls achieved by a single material. Thirdly, the end-of-life carbon emissions from 3DPC are significantly lower (−78 %) than conventional house. This is mainly due to the high level of recyclability of the 3DPC material, which is made possible by using a single material in printing walls. As a result, the benefits of 3DPC walls extend even beyond their life, with a remarkable 589 % increase in benefits due to the 100 % recyclability of the 3D-printed walls and their potential for use in printing new products.

On the other hand, the carbon emissions produced during the printing of the house are higher than conventional construction (51 %) due to the electricity consumed by pump and robotic arm stations. The source of electricity for this project was the national South African grid, which mainly generates energy from fossil fuel sources with high CO2 equivalent intensity (Moghayedi et al., 2023). However, by utilizing clean energy from renewable sources, it will be possible to significantly reduce the carbon emissions of the construction phase of the 3D-printing. This would, in turn, further reduce the life cycle carbon emissions of 3DPC houses.

The WLCA results provide compelling evidence that 3D-printing technology can enhance houses' environmental sustainability by significantly decreasing WLCA. This discovery aligns closely with the research conducted by Moghayedi et al. (2022), which showcased that technological innovations, including 3D-printing, are effective tools for advancing the environmental sustainability of housing.

*4.4.2.2. Life cycle cost analysis (LCC).* Similarly, the LCC of FU of 3DPC and conventional houses were calculated utilizing BIM 5D using actual quantities of materials and a local pricing database (AECOM, 2023). Table 6 presents the LCC analysis results for the FU of both houses

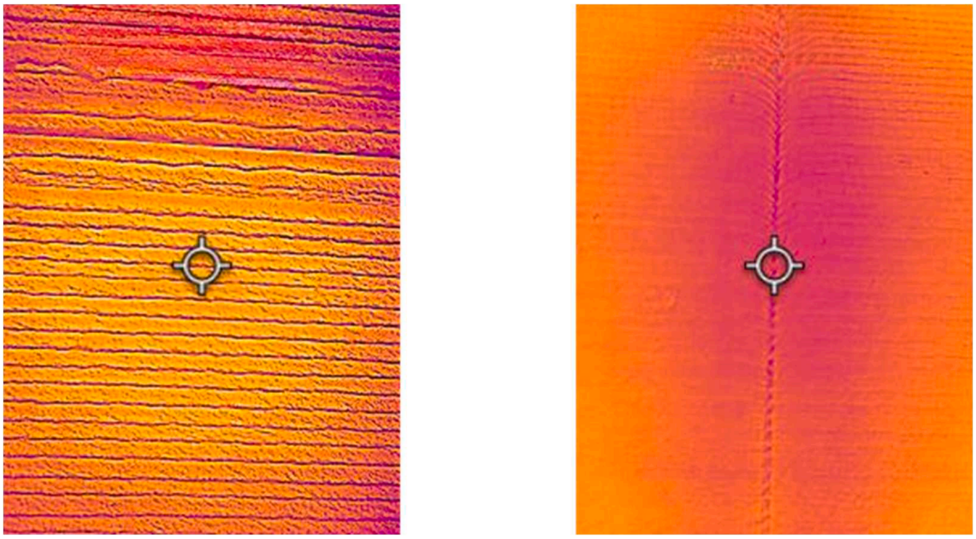
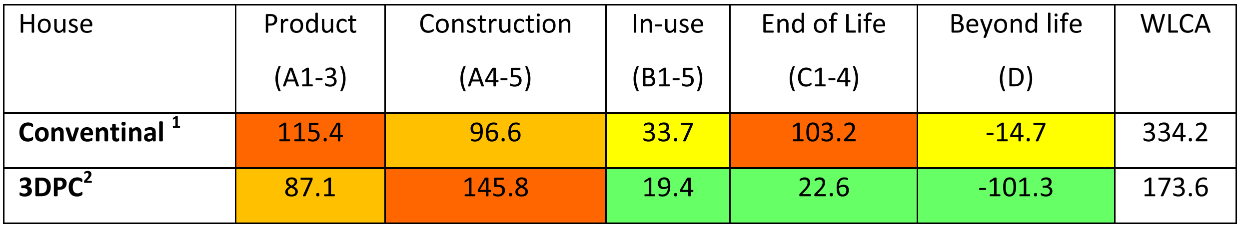


**Fig 13.** Infra-red thermograms of wall layers and joint between two wall elements.

**Table 6**
Whole life carbon assessment kgCO2e/m2 of the case studies (walling system).



| House | Product (A1-3) | Construction (A4-5) | In-use (B1-5) | End of Life (C1-4) | Beyond life (D) | WLCA |
|---|---|---|---|---|---|---|
| **Conventional** [1] | 115.4 | 96.6 | 33.7 | 103.2 | -14.7 | 334.2 |
| **3DPC**[2] | 87.1 | 145.8 | 19.4 | 22.6 | -101.3 | 173.6 |

(walling systems). A heat map in Table 7 uses a color scale to identify building stages associated with high costs easily.

As shown in Table 7, the material cost of a 3DPC house significantly surpasses that of bricks and mortar (1521 %), primarily due to the use of proprietary imported materials. While the maintenance cost for 3D-printed walls is lower than for bricks and mortar due to the employment of a single material, the overall maintenance cost is slightly elevated (20 %) due to the expensive proprietary materials incorporated in this system. Additionally, the equipment cost for 3DPC stands considerably higher (365 %) when compared to conventional house.

Nevertheless, the labor cost for 3DPC is notably lower (78 %) than the conventional house, attributable to its threefold faster delivery (8 h vs 3 days). Furthermore, the use of a single material in 3DPC walls facilitates 100 % recyclability at the end of the house's lifespan, leading to significantly reduced recycling costs (59 %) compared to bricks and mortar.

It is crucial to highlight that, despite the recycling advantage, the overall life cycle cost of a 3DPC house remains 381 % higher than that of a conventional house, primarily due to the utilization of proprietary materials in this research. Nevertheless, through the strategic utilization of local and bio-based materials, such as earth materials, the LCC of 3D-printed walls is projected to experience a significant reduction, making it a more cost-effective option in comparison to conventional bricks and mortar. This is further affirmed and substantiated by research conducted by Yang et al., Chen and Li (2018) using cost calculation methods of construction against 3D concrete printing.

## 5. Discussions

This study aimed to evaluate the building performance and sustainability of a 3D-printed affordable house, comparing it with a conventional low-income house in Africa. The results, based on direct observations of thermal performance, humidity, and airtightness, along with whole-life carbon and cost assessments, unequivocally show that the 3D-printed house outperforms the traditional low-income house in terms of overall technical and sustainability aspects.

The findings demonstrate that the labor-intensive nature of conventional housing in Africa leads to slow delivery, high material wastage, poor quality and efficiency, and increased incidents and accidents (Moghayedi et al., 2022). These challenges contribute to a housing backlog and significantly impact sustainability and residents' quality of life, exacerbating the housing crisis in Africa.

While various scholars have highlighted the advantages of 3D-printing technology in the housing sector, none have systematically evaluated the actual building performance, and holistic sustainability assessment includes WLCA and LCC. For the first time, the results of this study affirm the previously held belief that 3D-printing offers a viable solution for addressing the housing crisis in Africa. 3D-printing not only enhances the technical aspects of housing projects but also significantly improves the three aspects of sustainability—economic, social, and environmental—despite a few critical challenges.

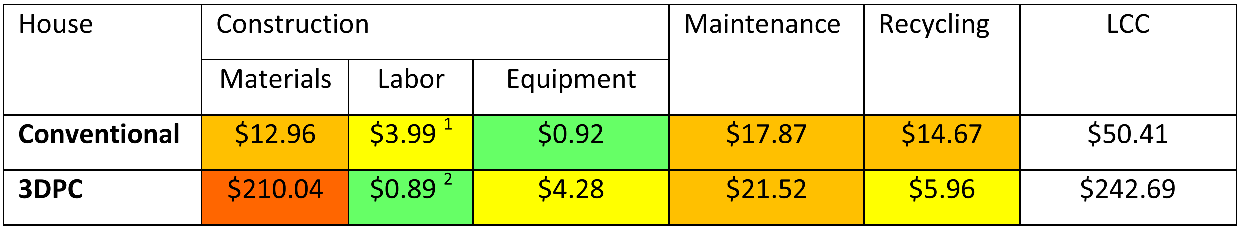
### 5.1. *Technical aspects*

The 3D-printing process for affordable housing demonstrates its ability to enhance flexibility and buildability. It enables adjustments in design and printing processes to accommodate passive techniques, cultural considerations, and end-user preferences. This mass customization feature improves technical aspects, structural integrity, overall quality, and efficiency of housing, as reported by previous scholars (Mahachi, 2021; Bazli et al., 2023). The precision and structural integrity achieved, along with the automation of intricate designs, contribute to an overall enhancement in the technical aspects and quality of African housing.

The findings demonstrate that 3D-printing technology expedites the digitalization and modernization of the African housing sector, reducing labor requirements by 72 %. This transformation, achieved by eliminating unskilled labor and reducing semi-skilled labor needs by 30 %, shifts the sector from labor-intensive to technology-intensive. This addresses housing issues related to human errors, defects, accidents, poor product quality, slow construction processes, and high labor costs. These findings are consistent with previous studies by Ahmed (2023), Tu et al. (2023), Bello and Memari (2023), Strommen (2022), and Zhang et al. (2019). A key advantage of 3D-printing, highlighted in the analysis of two houses, is its ability to reduce construction duration by 76 %, as reported by various researchers (Bello & Memari, 2023; Leschok et al., 2023; Tay et al., 2017), positioning it as a potential solution to address the housing backlog in Africa.

The technical analysis revealed minimal materials wastage (8 %)

**Table 7**
Life cycle cost USD/m2 of case studies (walling system).



| House | Construction | | | Maintenance | Recycling | LCC |
|---|---|---|---|---|---|---|
| | Materials | Labor | Equipment | | | |
| **Conventional** | $12.96 | $3.99 [1] | $0.92 | $17.87 | $14.67 | $50.41 |
| **3DPC** | $210.04 | $0.89 [2] | $4.28 | $21.52 | $5.96 | $242.69 |

with 3D-printing technology. Process optimization and skilled operators can potentially eliminate materials wastage, addressing a major issue in African housing projects. This zero-wastage aspect is supported by studies conducted by Strommen (2022), Tu et al. (2023), and Zhang et al. (2019).

Observations reveal superior building performance of the 3DPC house in both summer and winter compared to conventional low-income housing, as supported by Marais et al. (2021) and Sun et al. (2021). The thermal performance exhibits promise, with a 10 % improvement in distribution and a 13 % reduction in humidity. However, challenges persist in winter, necessitating insulation in 3DPC walls to meet recommended standards. Addressing thermal bridges is crucial for enhancing energy efficiency.

### 5.2. Economics aspects

The economic analysis highlights both the advantages and challenges of 3D-printing in African housing projects. 3DPC achieves a notable 78 % reduction in labor costs, consistently supported by various researchers, including Zhang et al. (2018). Despite significant labor cost savings, challenges arise in material costs, particularly with proprietary imported materials, contributing to a 1520 % escalation. The findings also show that equipment costs are higher by 3DPC (365 %), reflecting the initial investment required to adopt this technology. Higher materials and equipment costs for 3DPC also align with findings from other research projects (De Schutter et al., 2018; Nodehi et al., 2022).

Despite higher upfront and material costs, LCC suggests future cost reduction potential. The study underscores 3D-printing's capacity for recycled materials, with the 3DPC achieving 100 % recyclability, reducing recycling costs through uniform materials. Findings reveal that the 3DPC house's overall life cycle cost is 381 % higher than a conventional low-income house, highlighting the trade-off between material, equipment costs, and labor expenses, accentuating a cost challenge in Africa due to a lack of local technology and materials.

Promising cost reduction avenues include local technology and material innovation in Africa. Incorporating local and bio-mediated geomaterials is crucial for enhancing cost-effectiveness, as suggested by prior studies (Kreiger et al., 2019; Yang et al., 2018). Achieving economies of scale in manufacturing 3D printing technologies and implementing mass production strategies can significantly alleviate technology and project overhead costs, as indicated by research outcomes and prior scholarly works (Ma et al., 2018).

### 5.3. Environmental aspects

The research findings underscore the environmental sustainability of 3D-printing in the housing sector. There is a 48 % reduction in WLCA, with a 24 % decrease during production (attributed to recyclable materials) and a 42 % reduction during use phases (enhanced building performance and airtightness leading to lower energy consumption). These reductions align with prior studies (Bazli et al., 2023; Mohammad et al., 2020).

The WLCA shows the high circularity of the 3DPC house, with a 78 % reduction in end-of-life phase carbon emissions and a substantial 590 % increase in carbon offsetting during the beyond-life phase. This is due to the inherent recyclability and reusability of 3D printing, contributing to environmental sustainability and the potential for Net-Zero carbon houses, significantly enhancing the circular economy of African housing projects.

Challenges include higher emissions during construction, up by 51 % due to non-clean electricity use in printing. Transitioning to clean energy sources in Africa is crucial for improving the environmental footprint of 3D printing, offering potential reductions in WLCA through the adoption of renewable energy over fossil fuels (De Schutter et al., 2018).

### 5.4. Social aspects

In the realm of social aspects, the adoption of 3D-printing technology in African housing projects brings about a transformation in workforce dynamics. The elimination of unskilled labor and a 30 % reduction in the need for semi-skilled labor, combined with opportunities for upskilling and reskilling of construction workers, presents a positive social impact, as indicated by the study results. The potential for local employment, especially through short training courses tailored for 3D-printing projects, aligns with the goal of creating sustainable jobs within communities, as also emphasized by prior research (Mahachi, 2021).

Recognizing the direct correlation between the presence of unskilled labor on-site and the frequency of incidents, a substantial reduction in the number of these workers can significantly enhance the safety of housing projects, thereby improving the social sustainability of the African housing sector.

The study's findings clearly demonstrate that the building performance, quality, efficiency, and operating cost of the 3DPC house surpass those of conventional low-income houses in Africa. This substantial improvement enhances end-user satisfaction and overall elevates the quality of life for low-income households, a crucial and marginalized population on the continent.

Nevertheless, the thermal performance assessment underscores the need for insulation to meet recommended standards for user comfort during winter nights. Additionally, the study emphasizes the importance of addressing thermal bridges and enhancing airtightness to improve building comfort further. Proactively understanding and addressing these aspects will elevate African affordable housing to high-performance standards, which is crucial for the well-being and health of users. Consequently, this will foster greater user acceptance and satisfaction with 3D-printed houses.

Another important social aspect of 3D printing is its ability to integrate the needs and preferences of end-users in the design of housing (customization) without adding to the cost of the house or extending the duration of housing delivery, as also reported by previous studies (Ma et al., 2018; Mahachi, 2021).

## 6. Conclusions

In conclusion, this study makes a substantial and timely contribution to the ongoing discourse surrounding the adoption of 3D-printing technology in African housing projects, addressing persistent inefficiencies and the formidable housing backlog on the continent. The research, designed to achieve specific objectives, meticulously examined the building performance and whole life cycle assessment of a real-size 3DPC house. These results were then systematically compared with those of a conventional low-income housing unit in Africa, shedding light on critical aspects that demand attention within the affordable housing development process.

Notably, the study underscores the imperative need for continuous and consistent innovation throughout the affordable housing development process, especially considering the prevalent supply-related challenges associated with these housing endeavors. The findings reveal that the building performance of the 3DPC house, particularly in terms of thermal and humidity aspects, slightly outperforms its conventional brick-and-mortar counterpart, a common construction method in low-income housing projects across Africa.

The WLCA assessment further unveils that the 3DPC house exhibits significantly lower carbon footprints across its entire lifespan, thus underlining its environmental sustainability. However, the study emphasizes the nuanced nature of the findings, noting that while the 3DPC house presents promising environmental benefits, its overall life cycle cost remains higher. This cost discrepancy is primarily attributed to the initial financial investments associated with technology adoption and the use of proprietary printing materials, factors contextualized within the African setting.

Despite the existing cost challenges, the study optimistically points to ongoing trends of technological advancement and the scaling up of 3D-printer manufacturing, which have been instrumental in steadily reducing costs. Additionally, active research endeavors focusing on the exploration of local bio-based or recycled materials for 3D-printing show promise in mitigating cost disparities in the foreseeable future. The economic viability of 3D-printing is further underscored by evidence demonstrating that mass production of housing projects can effectively curtail equipment and overhead costs associated with implementing this technology. This suggests that, as 3D-printing continues to gain momentum and achieve economies of scale, it has the potential to emerge as a more cost-effective and sustainable solution for African housing projects, gradually overcoming the currently high life cycle costs.

Based on these comprehensive findings, the study concludes that 3D-printing technology stands as a sustainable mechanism, substantially improving building performance, overall economic, social, and environmental sustainability, and the pace of African housing projects. The research recommends the judicious use of innovative technologies like 3D-printing, coupled with locally sourced bio-based materials, to be considered by housing stakeholders as a transformative approach to address the housing crisis in Africa. This strategic combination has the potential to not only reduce costs but also expedite housing delivery through mass production, ultimately leading to the development of sustainable, innovative, and affordable housing that enhances the quality of life for occupants.

Furthermore, the study emphasizes the critical importance of localizing materials for 3D-printing to promote its wider adoption in modern construction methods for delivering sustainable and affordable housing. To support this transition, the study suggests that African governments must provide financial incentives, formulate policies encouraging the adoption of IBTs and bio-mediated geo-materials, and support local manufacturing of 3D-printers. Additionally, investments in research and development tailored to local contexts, along with capacity building and training for housing designers and developers, will facilitate broader adoption.

This pioneering research makes a substantial scientific contribution by systematically evaluating the actual building performance and sustainability of a full-scale 3DPC house in comparison to a conventional low-income house in Africa. The study enriches the understanding of the technical intricacies associated with implementing 3D-printing in African housing projects, offering valuable insights into the practical challenges and advantages of this technology. The comprehensive evaluation of the WLCA and cost analysis introduces a holistic perspective to sustainability research, extending beyond technical aspects to encompass economic, social, and environmental dimensions.

Furthermore, the research establishes a strong connection between the limitations of conventional construction methods in addressing the housing crisis in Africa and the potential of 3D-printing as a transformative solution. By quantifying the advantages of 3D-printing, the study underscores the role of innovative technologies in alleviating housing crises. It pioneers the exploration of 3D-printing technology in the African context, shedding light on the unique challenges and opportunities specific to the region.

By highlighting the absence of building codes and standards for 3D-printing as a technical challenge, the research contributes to the discourse on the need for regulatory frameworks tailored to the adoption of advanced construction technologies in African countries. The study bridges the gap between theoretical discussions on the benefits of 3D-printing and the practical realities of implementing this technology in a real-world African housing project. This empirical grounding enhances the credibility and applicability of the findings.

The insights generated by this research serve as a foundation for guiding future studies on 3D-printing technology in housing and construction, encouraging a more nuanced exploration of its implications for various aspects of sustainability and performance. It sets a foundational precedent for future research endeavors seeking to evaluate the sustainability performance of various 3D-printing applications in diverse construction projects. Future studies could delve deeper into assessing the sustainability performance of 3D-printing in a range of housing and building typologies, exploring variations.

Moreover, there is ample scope for research to validate the potential of 3D-printing technologies in achieving Net-Zero and carbon neutrality targets in the construction industry and promoting cleaner production methods. This could significantly enhance the social, environmental, and economic aspects of housing throughout its entire lifecycle. Overall, this study offers a comprehensive and pioneering exploration of 3D-printing technology's potential in addressing the complex challenges of affordable housing in Africa, providing a roadmap for future research and practical implementation in the field.

## CRediT authorship contribution statement

**Alireza Moghayedi:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jeffrey Mahachi:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Refilwe Lediga:** Conceptualization, Data curation, Formal analysis, Software, Validation, Writing – original draft. **Tshepang Mosiea:** Formal analysis, Funding acquisition, Investigation, Supervision, Validation, Writing – original draft. **Ephraim Phalafala:** Formal analysis, Funding acquisition, Investigation, Resources, Writing – original draft.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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