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Review

3D printing for remote housing: Benefits and challenges

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ABSTRACT

Additive manufacturing and in particular, concrete 3D printing has been suggested as one of the interesting solutions to unlock remote development, enhance the strength and capability of the local and national manufacturing and construction industries, and offer fast recovery in post-disaster scenarios. In this study, the remote housing construction challenges with a particular focus on Australian Northern Territory (NT) are reviewed and the feasibility and efficiency of using concrete 3D printing to tackle those challenges have been discussed. Besides the advantages of 3DP for remote housing, it's limitations and concerns have also been presented. Finally, some completed 3D-printed construction projects in remote locations were introduced. According to the findings of this review, to establish whether 3D printing is practicable and desirable in remote locations, trade-offs between several aspects, including materials, structural design, process efficiency, logistics, labour, and environmental impact, must be taken into consideration. In the case of using local materials that meet the printability, buildability and robustness requirements, 3DP could be considered a cost-effective solution for remote housing. However, researchers, designers, and decision-makers should consider the options, such as remote on-site fabrication, available local materials and their quality, and the large-scale manufacturing process and concrete 3DP limitations when evaluating the feasibility of using 3DP in comparison to conventional construction methods.

1. Introduction

Rapid prototyping or additive manufacturing (AM), known as 3D printing, has been used for many years [1]. Charles W. Hull of 3D Systems Corp. developed the first functional 3D printer in 1984. In the beginning, the technology was prohibitively expensive and out of reach for most consumers. But as the twenty-first century began, prices plummeted, enabling 3D printers to penetrate numerous industries [2–5]. One of these industries is the building and construction (B&C) sector [6]. It is well known that the building sector both uses a lot of resources and causes a lot of pressure on the environment [7]. The building sector has also faced criticism for its poor productivity. For instance, when the labour productivity of 20 different countries was examined, it was discovered that the US performed the lowest, with an annual compound rate of −0.84%. Other industrialised nations including the UK, Singapore, and Hong Kong have also experienced low productivity in the building sector [8]. 3D printing has been suggested as a revolutionary construction method that could improve the construction sector productivity and as a results of industry's active involvement in the 3D printing market, the perception of the construction sector may alter.

From the perspective of construction, buildings are objects that can host 3D printing. The building sector has made numerous attempts to use this printing to boost personalisation, shorten construction time, and raise affordability. To create 3D architectural models, for instance, large contractors now have a suite of modelling tools and a printing process [9].

In addition to producing 3D models, contour crafting technology has advanced to enable the production of large structures [10]. This technique extrudes the interior and exterior skins of the wall, which are then backfilled with a bulk substance comparable to concrete. There are now just a few teams designing and building 3D-printed full-scale infrastructure, which limits the uses of 3D-printed construction [11]. The majority of research only speculatively consider how 3D-printed structures might be used in the future.

Popular uses of 3D printing include building emergency shelters, providing relief post-disaster accommodations, and providing affordable houses [12–16]. According to several studies, autonomous 3D-

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printing in construction may also be revolutionary in high-risk or remote locations, such as those with rocky terrain, unfavourable climates or hostile environments, and military locations [17–19].

Few research studies have examined the viability of 3D printing in rural and undeveloped places, although studies on 3D-printed structures frequently propose the use of this technology in these settings. Remote areas are typically difficult to reach and in many cases are also home to extreme environments that make the maintenance of human habitation prohibitive. In Australia's remote areas the Indigenous communities' ownership prevents home ownership which discourages non-community investment. It is evident that 3D printing in construction is a feasible choice under specific situations and even competitive with traditional construction in some cases, as demonstrated by the classification and contextualisation provided by several case studies. It's possible that 3D-printed building is most valuable in distant locations and when there is a pressing need to develop or restore operating capabilities. Social services during natural disasters in remote areas may prompt responsible organisations to take 3D-printed structures into account during their planning process.

Overall, this review will assist readers in comprehending the various features of using additive manufacturing and in particular concrete 3D printing as well as identifying the benefits and challenges of using 3D printing as one of the solutions for remote housing. Furthermore, it helps decision makers and stockholders to evaluate the feasibly and efficiency of using concrete 3D printing method for mass construction in remote areas.

2. Remote housing

. Numerous Aboriginal groups suffer extreme physical and mental tension, which is either directly or indirectly related to their living conditions. Lack of weather protection, living in cramped conditions, domestic violence, alcoholism, widespread health issues, and future uncertainties are related to the available housing [20]. Fig. 1 shows some remote houses in East Arnhem Land with poor design and lack of regular maintenance, which are unfit for occupation. It is generally known that there are serious issues with the planning and construction of Indigenous housing, particularly in Australia's rural and remote areas. The design of many houses in remote areas does not reflect the culture of the residents. They are frequently poorly constructed and maintaining and repairing them has never been done properly [21,22]. Additionally, Indigenous housing needs in remote communities are not specifically addressed by building design codes [23].

Housing improvements in terms of house numbers, appropriateness of cultural and environmental characteristics, and durability is regulated by Australia's federal and local governments, who do acknowledge that housing is "more than a roof overhead" [25,26]. A complex network of circumstances that have been in place for several years has led to the current situation with regard to remote Indigenous housing, as discussed in [23].

The challenges that must be addressed regarding the issues with housing in Australia's remote Indigenous communities are looked into in this section. The following are the most important elements that have been discovered to be essential to acceptable housing outcomes in remote areas:

2.1. *Challenges and issues*

In a predominantly metropolitan country, the distribution of Indigenous people is diverse. Compared to non-Indigenous, Indigenous people are less likely to dwell in large cities and towns and are more likely to reside in rural and remote places and Indigenous Australian who live in remote or very remote areas largely live in social housing than those in non-remote areas [27]. There are 1200 remote communities home to a total of 100,000 Indigenous Australians [28].

Three main interrelated sociodemographic aspects of Indigenous society exacerbate the issues that follow for housing policymakers and, particularly, for isolated Indigenous people.

1) Severe shortage of housing in remote areas:

Design and quality of housing, as well as chronic overcrowding, are widespread issues, particularly in remote Indigenous communities [29]. For instance, over 48% of Indigenous adults in Australian's remote areas live in overcrowded conditions [30,31]. Although NT Government reported that overcrowding in communities covered by the National Partnership has decreased from 58.1% in 2017 to 54.1% as of September 2021, such a percentage remains very high [32].

In some houses, more than 20 people need to live in a house [29] and simply in the NT, between 8000 and 12,000 more houses are needed by 2025 [33]. Shared areas, such as bathroom, kitchen and laundry facilities are heavily used by overcrowding, which frequently results in clogged drains, broken windows, and fixtures that are difficult to fix or replace with few competent labourers to hire. Because of this, design and construction must consider the robustness and the durability of the materials and the quality of the construction.

2) Indigenous population, a younger age structure than mainstream

In comparison to the non-Indigenous population, the average age of Indigenous people (20 years) is 16 years lower. Given that Indigenous Australians are younger than non-Indigenous Australians and that a bigger number of them are of childbearing age or close to it, the need for housing in remote locations will rise [34]. This indicates a critical need for young couples and single parents with one or two kids who want to leave crowded family homes and live independently. Expanded diversity

Fig. 1. Poorly designed and maintained Australian Indigenous housing (photograph: Kieran Wong, CC BY-SA) [24].

of housing options is also necessary to meet the independent housing demands of elderly people and young single adults.

3) Extreme shortage of employment in remote areas

While the unemployment rate was 14% in 2007, about three times the non-Indigenous people, the labour force participation rate for Indigenous people aged 15 to 64 years was 56% in 2002 [35]. As a result, the incomes of Indigenous families and households are significantly lower than the incomes of non-Indigenous individuals.

We now consider the 3D manufacturing techniques that their application in remote construction.

3. Additive manufacturing

3.1. 3D printing

The method of creating an object from a three-dimensional model by building up thin layers of material on top of one another is known as 3D printing. Fig. 2 displays a schematic 3D printing or additive manufacturing (AM) process used to construct houses. The International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) define AM as the process of combining materials to construct objects using 3D model data, often layer by layer [36].

The primary benefit of additive manufacturing is its capacity to build parts from CAD models, which mostly saves time and expense for prototypes [37]. AM systems were divided into Powder-Based, Photopolymer-Based, Solid Sheets Systems and Molten Material by Gibson et al. [38]. For AM, various methods have been employed. It is important to note that the only factor utilised to classify these processes is the type of material they utilise. Extruded material systems and powder-based systems are the two construction-related additive manufacturing approaches.

Concrete Printing (CP), Contour Crafting (CC), Selective Paste Intrusion (SPI), Selective Binder (cement) Activation (SBA), and D-Shape are the five common types of 3D printing that are employed in construction [39–42]. The first two varieties are under the category of "Extruded Material Systems," whereas the final three are "Powder-Based Systems". In fact, concrete printing and contour crafting are similar in that the printed part is produced by injecting a mix (often mortar) through a nozzle (see Fig. 2). Except for the fact that the material is already fluid, and no heating is necessary, this procedure is comparable to Fused Deposition Modelling (FDM) methods. To feed the mix through the nozzle, a pump is necessary. For the SBA technique, a dry mixture of extremely fine aggregate and binder (cement) is used. The binder is locally activated by spraying it on the packed particles in a specific area, generating a cement paste matrix around the aggregate particles. The selective paste intrusion procedure involves injecting the binder (a paste made of cement, water, and additives) selectively onto the particles. To cover the crevices between the particles, the cement paste ought to be liquid enough. The D-shape method prints large items using a printer equipped with several inline nozzles. With the use of sand and selective binder spraying, the printer constructs the object layer by layer. The printed layer, which is only employed to sustain the structure momentarily, is still surrounded by limitless sand. The particle bed's hardener component reacts with the binder, which is commonly a resin. [40,41,43].

3.2. Material used in construction 3D printing

To be compatible with the existing printers, the materials used in 3D printing need to meet a few requirements. Successful 3D-printing construction material must possess the following four qualities: a) Printability or extrudability, which refers to how easily a material can be forced through a 3D printer's pump [45]. b) Buildability, which refers to the deposited material's resistance to deformation under stress. c) Pumpability, which is the ease with which the material is pushed out of the printer's nozzle. d) Open time, or when the printability, pumpability, and buildability are within a reasonable range [16,39]. Other elements also have a role in the success of printing concrete on top of these characteristics. The qualities of the printed concrete are influenced by the printing speed, which also determines whether the layers have any weak joints. The general characteristics of concrete would also be impacted by the printing orientation [46]. According to the literature, polymer materials, cementitious materials, and metallic materials are the most common utilised materials in 3D printing [16,47].

Because printable concrete is still in its early stages, there is no

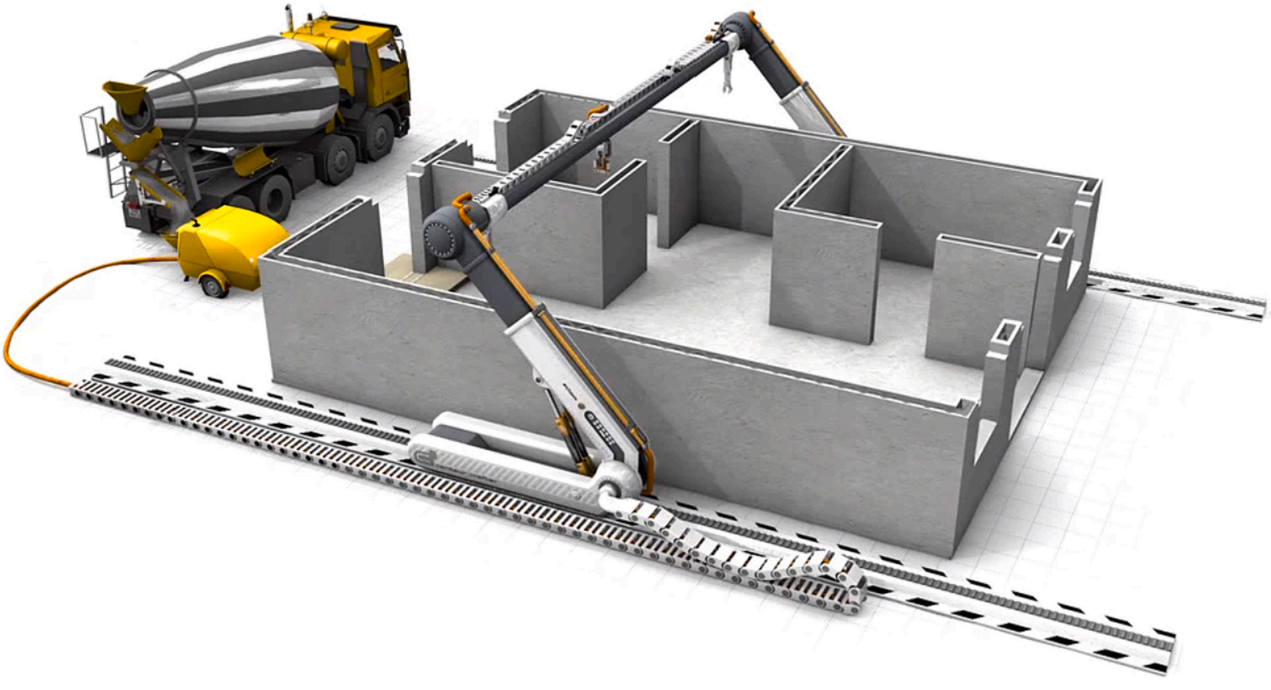


Fig. 2. Contour crafting printing for building construction [44] (Creative Commons Attribution (CC BY) license from MDPI).

standard composition [48]. In addition, since the nozzle size and printing resolution limit the size of the aggregates used in 3D printing, they are also known as printable mortar. Sand is the most commonly reported aggregate material in published research. In comparison to traditional concrete, printable concrete requires less water because of the required fresh properties lower slump, fast setting, and high strength [49]. Superplasticizers, accelerators, and retarders are used in the mix for controlling the workability of printed concrete. Cement is the most important component of concrete because it can bond the concrete mixture. The most common cement used in concrete is Portland cement, a mixture of clay, lime stone, and an eventual chemical collector of siliceous, aluminous, and ferrous nature [50,51]. The primary focus of concrete 3D printing in construction is the development of cementitious materials with appropriate formulations for buildability and printability. Fresh concrete's rheological requirements are the properties required for successful printing [52]. The rheological properties of printable concrete have been reported in terms of viscosity, elastic modulus, yield stress, rate of structuration, and critical strain [53]. A comprehensive study of the rheological requirements of fresh concrete has been carried out, beginning with the deposition process at the nozzle and ending with buckling stability and surface cracking after printing. The study summarised the rheological requirements for printable concrete as a function of printing factors [54].

Mahdy et al. [55] introduced SaltBlock, a sustainable and cost-effective composite manufactured from salt and sand, both of which are plentiful in Egypt's desert. The study revealed major challenges of SaltBlock 3D printing at an early stage of experimentation, in addition to concentrating on the potential of manufacturing a conventional material utilising a low-cost hybrid 3D printer that may be manufactured locally.

In a review paper, Bedarf et al. [56] emphasised the importance of porous materials, specifically foams, for construction as lightweight, high-performance, and insulating materials, as well as the important role they could play in current AM research for efficient construction processes and innovative building elements. Surprisingly, until now, only a few research projects have investigated the potential of large-scale 3DP with foams.

In the study of Bos et al. [57] the 3D concrete printing approach used by Eindhoven University has been thoroughly introduced, and several variations have been analysed and compared. The composition from linear continuous filament has introduced geometrical and structural properties. Discussions have been made discussing issues with experimental research. Finally, avenues for study and development have been found to enable practical use, and a view has been provided for the potential evolutions of these technologies.

Li et al. [58] showed that the use of locally accessible seawater and marine sediments in mortar and concrete for building construction may be a preferable option in remote islands and coastal areas lacking freshwater and river sand. Additionally, 3D printing of mortar or concrete may be used if there are no resources available locally for making the formwork. There is still a paucity of research on 3D printing with mortar or concrete generated from coastal sediments and seawater. To create 3D printable glass/basalt fibre reinforced saltwater coral sand mortars, a variety of mortar mixtures containing seawater, coral sand, and glass or basalt fibres were created and tested for their fresh and hardened qualities. All of the mortar mixes showed good buildability after the water reducer dosage was adjusted. The flexural strength was somewhat increased with the inclusion of glass or basalt fibres, but the compressive strength was significantly decreased. The printed specimens' flexural and compressive strengths, however, were noticeably lower than those of the conventional, unprinted examples. Overall, it was concluded that the 3D printable cement-based substance made from seawater coral sand and fibres shows significant promise for usage in distant locations.

Earth-based materials were used to produce a 3D-printed house by The World's Advanced Saving Project (WASP). Raw soil, rice husks, straw, and lime were the materials used. The materials used to build the house cost only 900 euros in total [59]. Concrete's effectiveness was greatly influenced by its quality and requirements.

As for the concrete mixes that would be compatible with 3D printing, Ghaffar et al. [60] cite that bulk elements like soil or crushed stone are typically combined with workability enhancers, Portland cement, or fly ash to create printed materials. A high-performance cement-based mortar has also been produced, by Le et al. [61]. Sand, water, and reactive cementitious compounds were used in the mortar mix. Cement, silica fume, and fly ash were used to make the optimum mix for high-performance printing concrete. Another investigation on the concrete mixtures for 3D printing showed that sufficient quantities of river sand and blends of limestone-based concrete and river sand are the types of aggregates that could be used successfully [46]. The river sand and limestone mixture yielded the highest strength [62]. However, it was found that the majority of mixes based on limestone could not be printed.

Generally, several materials have been used in construction using the 3DP method. However, for remote housing, several factors, such as feasibility and cost of the materials' transportation, local materials availability and printability as well as their short and long-term characteristics, must be taken into account before selecting the printing materials.

3.3. Robotic systems in 3DP

Large-scale 3D printers with a wider workspace and the ability to create 3D buildings at an industrial scale have undergone substantial advancement in recent years [63]. Systems that use a gantry to position the print nozzle in XYZ Cartesian coordinates are known as gantry-based systems. The enclosed volume of the gantry determines the build envelope of the system. Contour Crafting, Concrete Printing, and D-shape are some of the many well-known gantry methods [10,39,64,65]. The printing methods used by these three techniques vary; D-shape uses a binder jetting technique to selectively deposit binders on a powder bed made up of magnesium-based materials and sand, while Contour Crafting and Concrete printing use an extrusion-based method similar to the FDM in additive manufacturing. The utilisation of printing supports by Concrete Printing, as opposed to Contour Crafting's vertical extrusion of a planar structure, is another difference between the two processes that allows Concrete Printing to produce complete 3D topology.

In comparison to their gantry system equivalents, robotic arm systems are rather new. They give the end effector (print nozzle) more roll, pitch, and yaw controls, enabling the print nozzle to execute more articulate print patterns, including printing using the tangential continuity approach [66]. By maintaining a constant rate of curvature change, the tangential continuity approach creates a more aesthetically pleasant transition between print layers.

Using a Digital Construction Platform (DCP), Keating et al. [67] installed a robotic arm on a track-driven movable platform for the on-site fabrication of printed structures. By using solar panels to recharge its electrical driving system, DCP's technology is also self-sufficient. Cybe RC 3DP [68] is another mounted robotic arm system currently used. This system has a 6-axis robotic arm mounted on caterpillar tracks and was used in 3D printing the R&Drone Laboratory in Dubai.

Minibuilders [69] offers a substitute method for producing 3D concrete. Fig. 3 schematically shows the process used by Minibuilders to build structural buildings. Three little mobile robots are used in the system. The first robot has a sensor that follows a clearly designated initial path and pours the concrete foundation. Before printing additional layers of concrete and erecting the structure, the second robot is positioned on the foundation and secured to it with rollers. The final robot reinforces the printed structure that had only horizontal layers by printing vertically up the structure and using pressured air and suction cups [63].

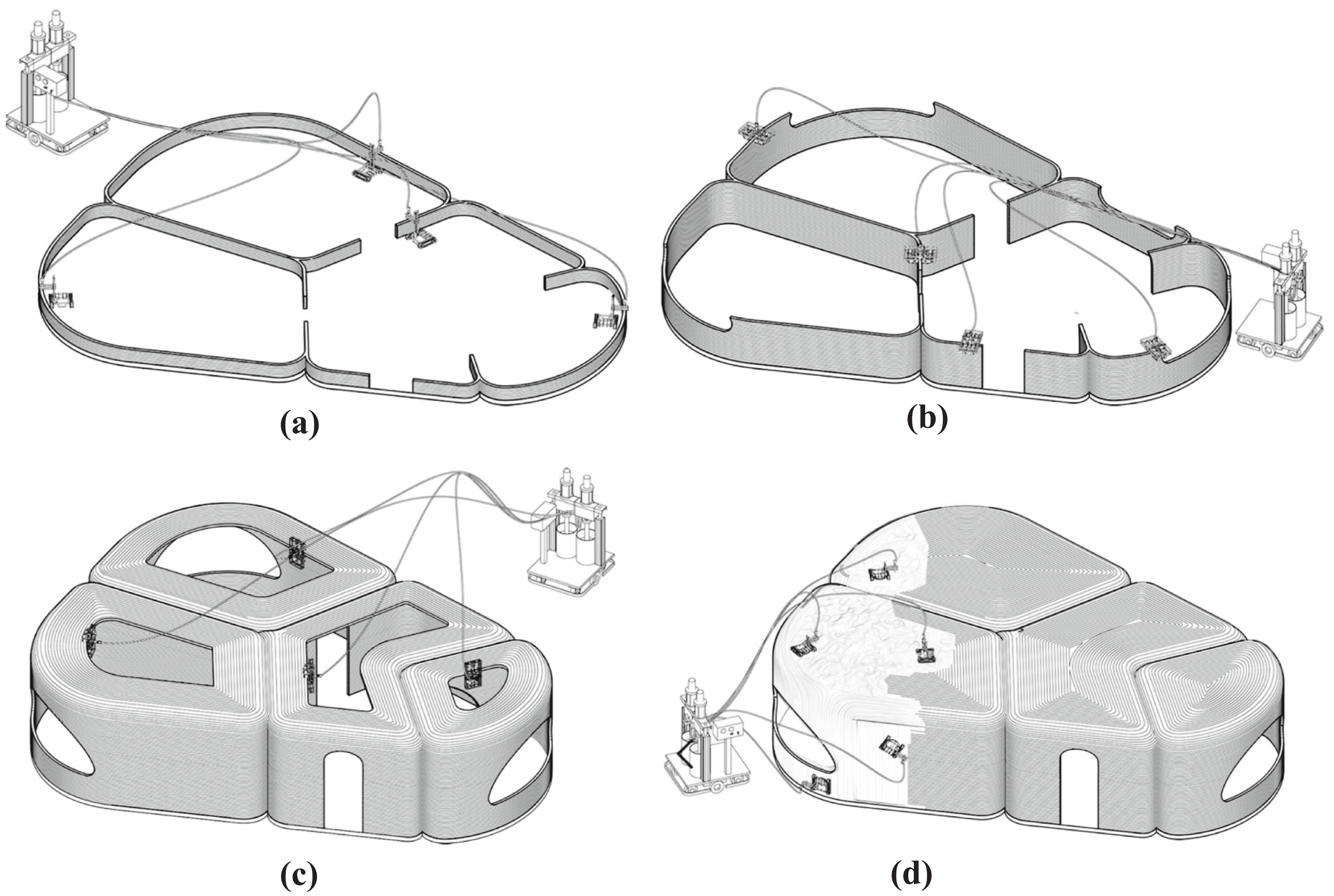


Fig. 3. 3DP process used by Minibuilders [69]: (a) Footprint (first 20 layers of the structure), (b) Walls, (c) Ceilings, and (d) Reinforcement (additional layers). Image courtesy of The Institute for Advanced Architecture of Catalonia (IAAC). Credits: Minibuilders is a project of IAAC, developed during Open Thesis Fabrication by Shihui Jin, Stuart Maggs, Dori Sadan, Cristina Nan, Saša Jokić and Petr Novikov.

3.4. *Design methods: 3D model*

A 3D model is required to 3D print anything. Building Information Modelling (BIM) is the most widely used software platform in the construction sector. To make projects more efficient, more productive, and safer, BIM uses communication technology and information to streamline project lifecycle procedures [70]. The programme is used to design the building, and materials and project expenses are entered to produce effective project planning. It is worth mentioning that BIM is already being used widely for design reasons in conventional construction projects [71].

It is necessary to translate the CAD file generated from the BIM programme into the machine language. Fig. 4 shows the process of printing a military structure by translating the CAD drawing into a BIM model [17]. The most typical format used is called STL, which stands for stereolithography, the original 3D printing method. The use of sustainable design seeks to improve the built environment's quality while minimising its harmful effects on the environment [72]. BIM in construction automation has been studied widely; some of these research studies looked into the creation of new algorithms to automatically enter as-built structures into the BIM software. Bentley Systems MicroStation and Autodesk Revit are two typical BIM applications used in the Architecture, Engineering, and Construction (AEC) sector [73]. The structural and mechanical features of the concrete, such as its density and compressive strength, must be introduced and considered in the BIM model for its use in 3D-printed construction projects. An increase in efficiency, productivity, and quality as well as a decrease in prices and lead times are all advantages of adopting BIM technology in 3D printing [70]. More energy-efficient design choices, quicker cost estimation, and shorter production cycle times are further advantages [74]. The use of the programme in construction does present certain difficulties, though. According to research conducted by Zhang et al. [73], just 46% of respondents believed that BIM had increased construction safety. This resulted from a lack of BIM data, notably safety analysis information.

4. Advantages of 3D printing for remote housing

4.1. *Construction timeframe and productivity*

The demand for the construction industry to become more productive and efficient while lowering costs, environmental impact, and resource consumption is growing [75]. Construction automation has demonstrated the ability to increase productivity in the construction industry. [76]. AM is viewed as a solution to productivity issues in the construction industry.

Any construction project must consider time. 3D printing clients gain various advantages from shorter construction durations, including an earlier start to the operations phase and income generation, lower overhead expenses, and more resources available for other projects. Construction moves along considerably faster than it does with conventional technologies [46,77,78]. This would enable mass production and expand the scope of the building. For instance, it was shown by Buswell et el. [9] that 3D printing enabled the production of a structural wall in 65 h as opposed to 100 h in the conventional framework method. A faster construction time as a benefit of 3D printing in construction has also been shown by several other projects [9,47,79–81].

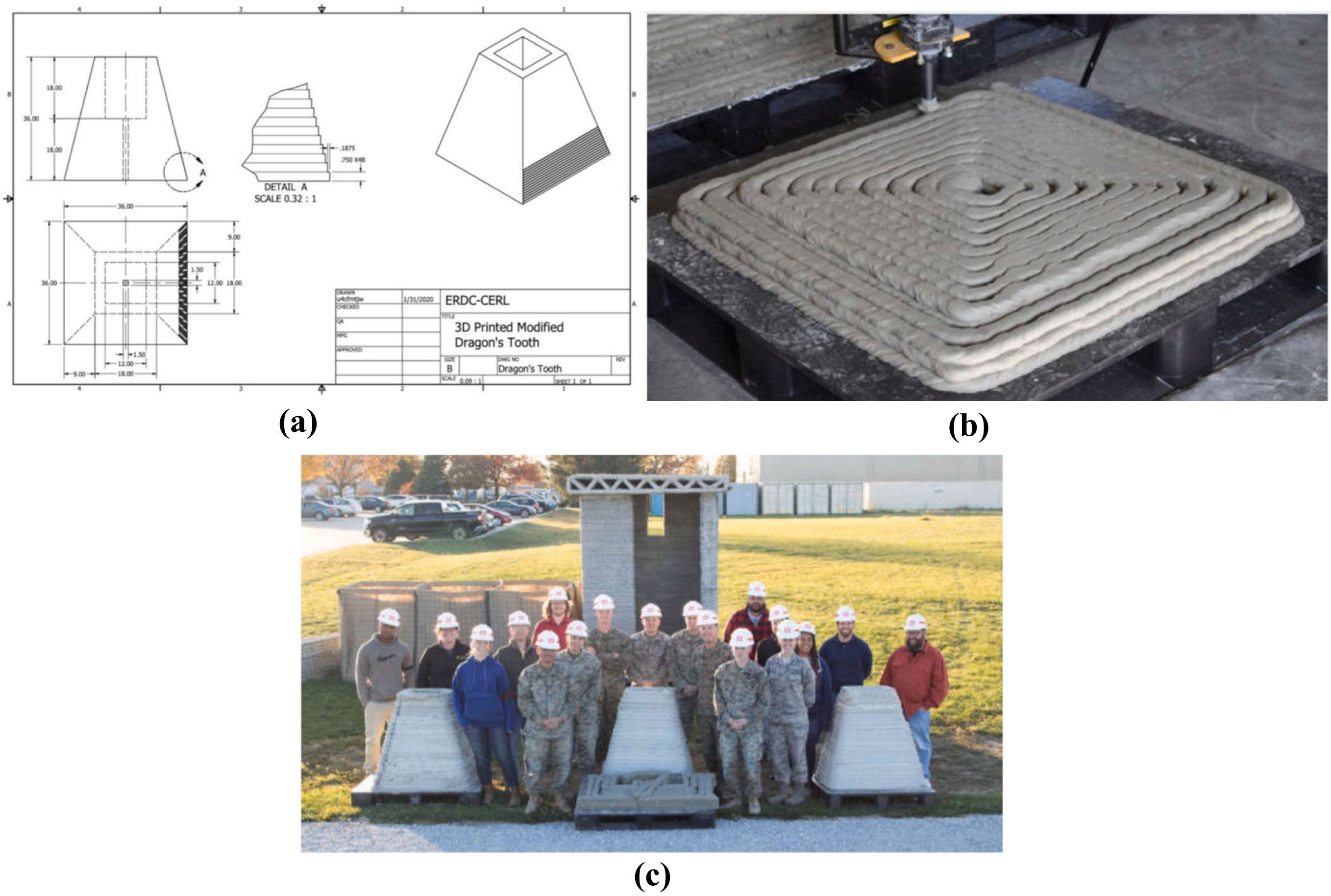


Fig. 4. 3DP steps (a) CAD model, (b) Printing process, (c) Final product [17]. (Creative Commons Attribution (CC BY) license from MDPI).

As mentioned in the Introduction there is a significant shortage of houses in remote areas (e.g. only in Australia's Northern Territory up to 12,000 new houses are needed by 2025 [33]). Such high demand and short timeframe make it very difficult and possibly expensive if conventional construction methods are to be used. Using 3D printing with such high-speed construction ability could tackle this challenge.

Moreover, the supply chain can be shortened when using 3D printing. By producing materials upon demand, 3D printing eliminates the waiting period for materials that require fast delivery. [16]. As a result, productivity is increased, which would have been reduced by late deliverables [16]. By using raw earth materials, the supply chain is shortened and lead times for materials are eliminated. The autonomous construction of building components from digital models with minimum human interaction or complex formworks has been one of the growing technologies that aims to decrease the supply chain in the construction sector [60].

Using local resources in construction as a strategy to encourage local participation in construction projects has been cited by Indigenous communities, as well as being a preferred material for the residents.

4.2. Project cost

There are several factors, including the type of material and printer, the location of the structure, the complexity of the structure shape, etc. affect the cost of 3DP construction significantly. However, for remote housing, 3D printing could reduce the cost of construction [8] in many applications. Costs associated with construction components, as well as those associated with transporting and storing resources, could be decreased [74,78]. The cost of labour is reduced because the machine only needs a limited number of operators if not one.

In a case study of a 3D-printed office in Dubai, the labour force consisted of seven individuals to install construction components, ten electricians, Mechanical, Electrical and plumbing (MEP) professionals and one individual to oversee the printer. Compared to an average structure of the same size, this office's labour costs were 60% lower [82].

Further, when the 3DP construction method was used, less labour-intensive operations compared to the conventional method in multiple sectors of construction were noticed [63]. In addition to lowering labour costs, 3D printing also lowers the cost of installing and removing formwork. Moreover, fewer site engineers in 3DP construction will result in lower supervision costs and faster construction will also cut down on indirect costs.

Table 1 shows a cost comparison between the conventional approach and 3D printing for building a wall out of 40 MPa concrete presented in Guowei et al. [42]. It appears that employing 3D printing to construct concrete components can almost eliminate the need for formwork and labour costs. Rough estimates suggest that the cost of formworks may

Table 1
Cost comparison between traditional and 3D printing methods for a wall made from 40 MPa concrete [42].

Item	Traditional method			3D Printing		
	Cost ($/m3)	Amount (m3)	Price ($)	Cost ($/m3)	Amount (m3)	Price ($)
Concrete	200	150	30,000	250	150	37,500
Pumping	20	150	3000	20	150	3000
Labour	20	150	3000	–	–	–
Formwork	100	1500	150,000	–	–	–
Total			186,000			40,500

account for between 35 and 60% of the total cost of concrete construction. Based only on the provided data, the total cost of a concrete wall produced using 3D printing is roughly a fifth of what it would be using a conventional building approach. However, the values presented in Table 1 are a rough estimation and a detailed cost assessment considering several effective factors, such as the structure location, the materials used, the type of robot, etc. is needed to better compare the cost difference between the 3D printed and conventional method. It is worth mentioning that the cost of housing in remote areas could significantly change compared to the values presented in Table 1. For instance, in Australia's Northern Territory the concrete price per m^3 is about 600 AUD, which is between 3 and 4 times more expensive than that of concrete used in urban projects. In addition, construction methods could significantly vary between urban and remote houses. Formworks are not typically used in remote housing, which may reduce the initial construction cost, however, material transportation and labour costs increase the final construction cost massively.

In Fig. 5 the breakeven point between additive manufacturing and conventional manufacturing processes is presented. In conventional manufacturing, the cost per unit reduces as the overall number of made items increases, whereas the cost per unit rises as complexity rises. On the other hand, the price of 3D printing largely stays the same. The number of units produced has little impact on each unit's production. Because of this, contemporary 3D printing excels in small- to medium-scale production and relatively complex structures. However, in the future, advancements in 3D printing acceptance and output will increase, and the cost of making 3D printing will gradually decrease [83]. It is important to keep in mind that the cost comparison between 3D printing and other traditional construction methods provided in Fig. 5 is a rough estimate given the numerous factors, such as the complexity and technology level of the printer, the type of materials, availability, and transportation, etc., that significantly affect the overall project cost. Therefore, to increase the reliability of the cost comparison, a thorough life cycle cost assessment (LCCA) must be done to consider the effect of all effective factors in the final project cost.

Currently, the cost of remote housing using conventional construction methods is significantly high. For instance, under a National Partnership between the Australian Federal Government and NT Government, the federal government committed to provide $550 million in funding to the NT Government from 2018 to 19 to 2022–23, of which $337.5 million were allocated for capital works to deliver a minimum of 1950 bedrooms. This was estimated as the equivalent of 650 three-bedroom houses (i.e. 520,000 AUD for each house) [32].

Recently, other construction methods, such as modular construction have been used to deliver some of these houses. NT government has estimated the cost of a three-bedroom building to be about $393,000, however considering the transport and installation costs, it has bumped up to over $535,000 for each house. That even exceeds the NT Government's target cost for a remote three-bedroom house, which was set at $500,000 [84].

Also, 3DP could reduce the cost of remote housing by reducing the need for external workers. 3D printers could be programmed remotely and trained local workers could facilitate the operation when human interference is needed on site. This is a significant cost saving considering the significant costs of flights to remote areas for construction workers. One more major cost-saving item will be materials shipment. Shipment of materials to remote areas often incurs considerable costs due to large distances to the resources and inaccessibility during the wet season. A 3D printer fed largely by local materials could reduce the dependence on material shipment. As an example, studies support that common earth in Australia's NT is suitable for earth construction [85] thus a well-designed mix of Portland cement and local earth could be suitable for 3D printing in such remote areas.

4.3. Flexibility in design, reconfiguration and modification

Compared to traditional methods, 3D printing technology has more geometrical and design freedom [8]. One of the benefits that picks interest in the technology is the ability to design and build structures that would not be feasible using conventional methods [9]. For instance, apart from the doors and windows, the 3D-printed house in Denmark printed by 3D Printhuset was constructed without any straight lines to demonstrate the amount of geometric freedom (Fig. 6). The expensive, curving buildings that are challenging to construct in other ways may be printed with great ease. As a result, architects may approach the design process with an open mind and achieve success. In the meantime, this advances the merging of the arts and architecture [47]. Buildings that are challenging to manufacture with the present conventional construction method can now be designed by developers thanks to 3D printing [10].

Several studies showed more freedom in geometry as a benefit of 3D printing and using BIM in construction [39,40,63,71].

Working with 3D models, such as the case of using BIM in construction, makes it easier to create 3D visuals, print 3D objects, and connect to virtual environments. In terms of remote housing, Arayici et al. [70] clarified how an architectural firm's adoption of BIM aids in reducing management and communication issues in remote construction projects. The paper uses a case study methodology to examine a UK Knowledge Transfer Partnership (KTP) project involving John McCall Architects (JMA) and the University of Salford, UK, in which the use of BIM between the architectural firm and the main contractor for a remote construction project was explained and justified. The adoption of BIM at the design stage was shown to significantly reduce the main management and communication issues, such as subpar construction work, lack of materials, and ineffective planning and scheduling.

The geometric freedom of 3DP makes it much easier for structural

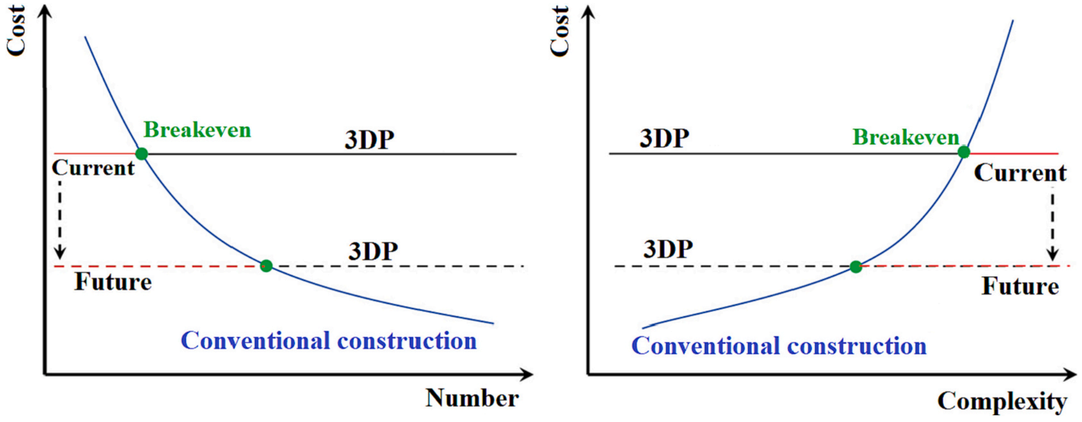


Fig. 5. 3DP Breakeven analysis comparing conventional and additive manufacturing processes. Image reproduced from [42].

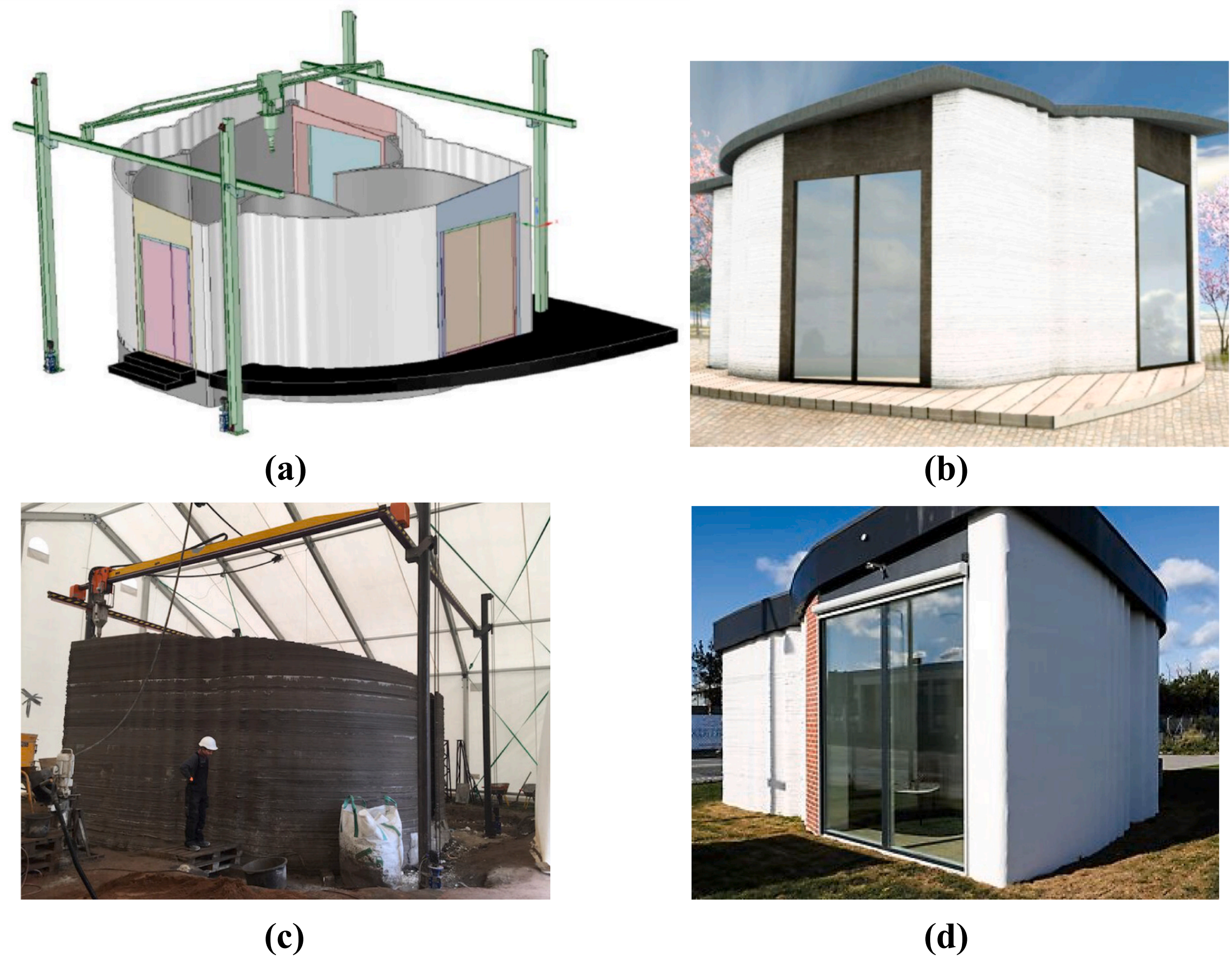


Fig. 6. The BOD ("Building on Demand") building in Copenhagen Harbour with curved 3D printed walls and sloped roof [86]: (a) Illustration of the 8*8*6 m concrete printer, (b) Rendered BOD, (c) Printing process, and (d) Finished BOD. Image courtesy of COBD International.

designers to implement the architectures, decision-makers, and the community's (i.e. residents') inputs in their design plans. This would also increase community engagement during the design process of the house, particularly in remote locations. Northern Territory Government (NTG) Department of Infrastructure, Planning, and Logistics (DIPL) of Australia considers community consultation to be a crucial stage of the community engagement [87] process which the Housing Reference Group uses to consult with locals and traditional owners to get their opinions on ideal architectural ideas. The acceptance of alternative designs could be increased by effectively involving the community in the early design stages, discussing them in sufficient detail and with sufficient elaboration, and involving everyone (particularly elders) in the design process.

The Australians Aboriginals 'architecture is distinctive within the several regional architectural traditions and is deeply localised. Indeed, with the resources available, shelters were erected. The three-eighth dome and the half-dome were two forms that were repeatedly used for economy and were adapted to their geographical location [88]. Thus, the Indigenous house design doesn't follow western norms [89] but technical staff working on remote housing are trained to design and build western buildings. With 3DP introducing more flexibility to the design, more community-oriented houses could be built.

The ability to modify remote homes if future modifications are required is referred to as flexibility. Ritual and cultural events, shifting cultures in some groups, inadequate resources, and brief lifespans [22,90], the need for a small family dwelling to include accommodations for extended families, varying demand for remote homes that are occasionally vacant as a result of Indigenous people migrating permanently or seasonally [91–93], and sometimes accommodating more than 30 people in a house [94] are good reasons for considering flexibility in remote houses. Some solutions are proposed in the literature or have been discovered following numerous real-world experiments and modifications in remote housing for more flexibility.

Rourke and Nash [95] highlight the value of yards and domestic landscapes in isolated homes as a reserve zone for gatherings with family, outdoor activities, and possible future changes in the home plan. For instance, to improve the liveability of existing homes, the NT government through the "Room to Breathe" project has allocated $200 million over 10 years (from 2016 to 2017 to 2026–2027) to build additional living spaces such as bedrooms, bathrooms, granny flats, and outdoor cooking places [96]. The main objectives of this project were reported as (i) ease the pressure of over-crowding in existing homes, (ii) allow homes to be better used, (iv) reduce wear and tear, and (v) provide an opportunity for family-based accommodation options. By removing the restrictions that block or steel frame walls impose on living spaces, using printed structures could increase the flexibility of isolated homes. The high design flexibility and construction speed of 3D printing could certainly help the successful delivery of projects like "Room to Breathe".

4.4. Local engagement

Community engagement in construction projects has been strongly supported for a variety of reasons including the importance of collaborative planning [21,97,98]; creating sustainable jobs for local people through community engagement in construction [99–101], the potential of training living skills; improving adults literacy and numeracy through engagement in practical tasks [101] and improving physical activities [102–104].

In a 3D printing housing project, most of the site staff could be selected from the community and with a short training course. In a 3D printing project, tasks that need tertiary qualifications or long training are usually done off-site. Although site staff in a 3D printing project are less than that in a similar conventional construction site, local people will have a better chance to engage in the tasks at the 3D printing site. This is because of the nature of 3D printing site activities which involve less training. To improve communication and local skills development, BIM, AR (Augmented Reality), and VR (Virtual Reality) can be used to communicate design with community members and train community people. Currently, DIPL employs BIM to create plastic 3D-printed models of the dwellings that are displayed to communities during the design phase.

In isolated places, social and cultural considerations are essential while consulting. When dealing with elders, community and community organisations should be compensated for their input, which should also include decision-making, as this affects the community's overall well-being [105,106]. Finally, when local materials are used in 3D printing, local businesses could be formed for material preparation and handling which enhances local engagement and creates local jobs.

The fact that locals frequently want homes that they have seen other people (in cities) live in is another obstacle to community engagement. Alternative designs with comparatively superior engagement opportunities are therefore challenging to deploy. Therefore, an engaging and flexible construction method, considering the community inputs and providing local jobs is necessary for remote construction. In this regard, additive manufacturing seems to have great potential to address these challenges to an appropriate extent.

4.5. *Sustainability and construction wastes reduction*

While remote communities' population relative to the whole nation is low [107], implementing sustainable practices in communities is critical and has been emphasised in different references [108–110]. Considering the very low income and uncertain occupation [111,112], electricity bills could be a major cost in communities. Further, maintenance of the electrical devices and air conditioners, in particular, could incur significant costs to the government. Therefore, sustainable and energy-efficient residences in remote communities are essential in improving the quality of life and reducing government costs. The high cost of construction and waste disposal in remote areas also obliges the decision-makers to improve the longevity of the structures in those areas. At present, the average lifetime of structures in some communities is less than seven years [22]. Moreover, most communities in NT use bore water [113] thus, inappropriate waste management could contaminate the water resources in the communities. Sustainability in remote construction is also important when the preservation of the Indigenous heritage and their sacred areas is concerned [33].

3D printing in construction is deemed a sustainable and economically friendly method [78]. The decrease in waste is one of the ways it is more environmentally friendly than conventional techniques (this will be explained in more detail in the next section). In addition, sustainable materials could be used in the 3D printing mix. For instance, the walls in a 3D-printed house in Denmark were insulated with recycled cellulose fibre, and the concrete mix used in construction included recycled elements like tiles [114].

A further factor contributing to the sustainability of the constructions is the potential use of low-impact materials like geopolymers and raw earth materials. The Perrot Group [115] evaluated the viability of printing structures using earth-based resources. The results demonstrated that great productivity was attained by incorporating alginate into the soil minerals. The compressive strength of the printed sample was found to be similar to the conventional earth-based sample [115]. Geopolymers have also demonstrated the potential for enhancing sustainability [116]. WASP has developed geopolymer-based 3D-printed structures [114]. Furthermore, Xia et al. [117] looked into the possibility of substituting conventional Portland cement with geopolymers as a 3D printing material. It was reported that the production of geopolymers emits 80% fewer greenhouse gases than the manufacture of Portland cement and lower CO_2 emissions could be achieved. As a result, the energy used for construction was significantly reduced, and manufacturing efficiency was increased [47].

Sustainability is critical in remote housing [108–110]. When the population in remote places is compared to the national population, e.g. for Australia less than 2% of the nation's population, sustainability of remote residences does not initially appear to be a significant difficulty [107]. However, when one considers the rate of house deterioration in remote places and the relevance of preserving natural and cultural sites in these areas, the significance of environmental integrity in building in remote communities becomes apparent [22,33,90].

Enhancing flexibility in the structure so future alteration could be accommodated with the current design has been found as one of the solutions to enhance the sustainability of remote housing. This would significantly reduce material waste in remote areas given the varying size of households in most remote communities.

Modular 3D printing construction could increase flexibility and consequently sustainability by allowing the house to be disassembled and used for a rebuild, for instance in the event of house damage after natural disasters. In addition, 3D printing could be used so that extra rooms can be attached to existing houses in an easy process [105].

The technology of 3D printing decreases the amount of waste produced during construction [8]. Because the process uses additive manufacturing, the materials are tailored to the result created, producing almost little waste. [118]. In addition, 3D printing utilises raw materials such as sand, which can be easily re-used [60]. According to estimations, 3D printing reduces construction waste by between 30 and 60% [83]. When compared to conventional methods, wet construction operations are avoided in 3D printing construction and lightweight structural components available to the construction industry result in lowering waste production, pollution (less dust production), and global resource consumption [75,78,119].

In addition, due to the nature of 3D printing construction, compared to the conventional construction methods, significantly lesser change in the intact areas is needed. This further reduces the produced construction waste amount.

4.6. *Formwork elimination*

According to Camacho et al. [16], another significant advantage of using AM in construction is a decrease in formwork. In the case of using 3D printing, the wastes that would have been produced by using formworks in the conventional method, are removed. Without the use of formwork, AM construction directly moulds and forms the structure on the job site. In addition to the time and cost savings, this will have positive environmental benefits as well. For instance, no wooden formworks despite the conventional concrete pouring, means no trees are used and thus less negative environmental impact [16].

Eliminating frameworks in 3D printing construction in remote areas will provide several advantages, such as: decreasing the onsite labour number and reducing the accident risk of assembling and disassembling formworks, especially at elevated levels, as well as reducing the construction time and cost associated with formworks transportation.

4.7. *Safer sites for local community workers*

Because of injuries and fatalities during construction that result in significant losses for people, companies, and societies as a whole, safety is considered a major concern [84]. Due to the printers' ability to handle the majority of hazardous and risky tasks, 3D printing lowers the number of accidents and fatalities that occur on-site [78]. This advantage arises from the ability of 3D printing to automate the construction process. Generally, by removing on-site workers from dangerous locations and automating some building operations, AM offers safety-related services to the construction sector [16].

Applying Design for Manufacturing and Assembly (DfMA) principles to remote buildings and using modular 3D printing construction methods could also increase community workers' safety and involvement in construction projects. Building components could be produced off-site and designed with standard geometries. The components could then be put together by trained locals. This could require a variety of simple skills, such as measuring, matching, giving instructions in audio format, operating forklifts, etc. This will significantly reduce the injury risk during construction and increase community engagement and willingness to participate in construction activities.

4.8. *Printing non-structural elements*

In a remote area, due to transportation challenges, providing furniture is a serious challenge. The cost of transporting brand-new furniture to remote areas is often so high that Indigenous people mostly decide to manufacture their furniture using local materials, such as wood and soil. The possibility of printing furniture right after printing the house could be a cost-effective solution to provide robust and long-lasting furniture.

5. Challenges

5.1. *Social challenges*

The previous section explored the several advantages of 3D printing in the building industry. The use and advancement of 3D printing in the building industry are still in their infancy and confront numerous obstacles. As with any new technology, the downsides of 3D printing are considerable. Among the social downsides is the impact on the existing construction workforce. 3D printing will reduce the number of construction employees required. Although this is a gain because it cuts labour costs, it is a disadvantage for those construction skilled workers whose jobs are threatened such as workers pouring concrete and installing steel rebar cages. This could lead to societal issues in some construction-dependent areas.

5.2. *End product appearance*

3D printed surfaces are often rougher than conventional moulded concrete surfaces. Due to design and material limitations, 3D-printed structures may not meet the expectations of end users at the current technological level. The chamber volume of the 3D printer strongly restricts the size of the design. Currently, 3D printing is unsuitable for large-scale endeavours. There are also geometric limitations where the printer's capabilities are restricted.

5.3. *Initial cost*

Another downside could be the initial expense, as 3D printing is currently an expensive construction method. The initial cost of the equipment may be expensive. The transportation of the printer is both difficult and relatively expensive. For the concrete to be able to pass through the robot's nozzle, it must be workable, i.e. higher slump compared to conventional concrete; this may need a weaker or more expensive form of concrete.

However, in remote areas, in addition to the typical construction aspects, the total cost of the project depends on several other factors, such as construction location, the number of local materials used, the number of local workers, etc. Therefore, case studies are required to compare the final project cost of remote housing using the 3D printing method and the conventional method. Further, while there is a huge demand for remote housing in Australia [33], remote construction sites are usually far from one another. This means that small jobs in different places should be done over a very large area, almost a continent! With the high initial costs of 3D printing, deploying 3D printers to several places will be prohibitive. In this regard, a well-designed network of equipment hubs as proposed in [120] could significantly reduce the costs of equipment shipment.

5.4. *Materials suitability*

Another downside of using 3DP for construction is the restricted availability of suitable materials. In 3D printing, the materials used need to meet certain requirements to be compatible with the technology. Buildability, printability, and open time are significant challenges in terms of 3D printing materials. For instance, appropriate concrete for 3D printing requires unique specifications that are significantly different from those for traditional concrete structures [46]. The material challenge becomes significantly bigger when the structure is located in a remote area. If the local materials could not pass the specification requirements (e.g. not buildable or printable), transporting 3DP desired materials from other locations would increase the construction cost and eventually reduce the economic efficiency of using 3DP for such a remote location. In NT, the soil doesn't change much in different communities [85]. Therefore, if local soil is successfully used in developing 3D printing materials in a community, the mix recipe could be used in other communities with minimum adjustment.

5.5. *Building services*

Utilities are not normally included in 3D printing and should be installed externally on the building. This generates additional work for MEP installation in the building. For example, the fact that building services like plumbing and electrical were not included in the 3D printing process presented a challenge in two Winsun projects. As a result, more work had to be done, which negatively impacted the structural integrity of the building [8]. This drawback will be more significant when it comes to remote locations due to the lack of skilled workers and the cost associated with human resources and facilities transportation. Some 3D printing companies, however, claim that 3D printing enables the integration of already created components into constructions, such as piping into printed walls.

5.6. *Structural integrity*

Because of the brittle character of the printed pieces, printing load-bearing components has proven to be difficult [121]. The main issue is whether it is possible to establish a general approach to attain adequate robustness and ductility for structural applications [57]. Given that voids might occur between filaments to degrade the structural capabilities, the layered structure is likely to be anisotropic [45]. The link between layers and filaments likely affects how concrete components behave once they have solidified. Bonding between layers is essential in many 3D printing applications, particularly when manufacturing concrete [122]. For instance, the structural performance of contour-crafted walls is significantly influenced by crack formation and propagation [122]. Therefore, the primary goal in concrete 3D printing is to achieve high strength in flexure, compression, and tensile bond. Furthermore, a low shrinkage is necessary since the freeform components are constructed without the use of forms, which could hasten the concrete's evaporation of water and cause cracks [45]. The possibility of shrinking and cracking may also be increased by the lack of available coarse materials. There is a lot of interest in improving the structural integrity of the 3D-printed structure as AM and rapid prototyping in building both grow quickly [122]. According to some research, the current technology may not be suitable for usage in large-scale models or buildings due to the stability and strength of printed goods made using current printing materials [8].

Structural integrity and strength will become more important when the structure will be subjected to extreme loadings, such as cyclones, earthquakes, floods, etc. For example, in Australia's northern territory remote houses are frequently subjected to floods and extreme winds (e.g. cyclones). Therefore, 3D-printed house prototypes must be tested for strength, integrity, and stability as per available standards/codes against such extreme loadings before widely being used in remote housing.

5.7. *Structural durability*

Mechanical properties of 3D printed elements could change over time. Several variables, most notably design accuracy, material quality, and environmental aggressivity affect the durability of 3D printed structures and may cause or contribute to their rapid performance decline over time.

In light of this, Grassi et al. [123] discussed the design-to-production process for a façade shading system utilising additive manufacturing as well as the related testing campaign to evaluate the viability of the design and the material durability. With this regard, they conducted tests on several polymers in a climatic chamber at Politecnico di Milano to monitor material performances over time under high temperatures, such as those in Dubai, to choose the best suitable 3D-printable material [123]. The Mercury Intrusion Porosimetry MIP results demonstrated that all samples, regardless of composition, have an equal total porosity. However, there are significant differences in the pore size distribution and morphology between printed and non-printed specimens.

A thorough investigation was done by Zhang et al. [124] into the 3D-printed cement-based samples' compressive and flexural strength, resistance to frost damage, chloride ion penetration, sulphate attack, and carbonation. To find the distribution of voids and to understand the macro-behaviour of specimens, MIP and X-CT imaging were used. According to CT findings, it was found that the voids in 3D Printed Concrete (3DPC) are mostly interconnected or even continuous among the concrete filaments; 3DPC has lower tensile strength than Moulded Concrete (MC) but greater compressive and flexural strength; 3DPC specimens have less long-term drying shrinkage than MC specimens. In comparison to MC specimens, 3DPC shows less resistance to freeze-thaw and chloride ion migration, but superior resistance to sulphate attack and carbonation. The majority of voids in 3DPC are connected to one another or are continuous, which could result in corrosion from within the matrix based on a freeze-thaw test, a deeper migration based on a rapid chloride ion migration test, and a continuous improvement at the initial stage based on a sulphate attack test. Generally, it was concluded that the toughened characteristics and durability of 3DPC are influenced by the void connections and their preferred orientation among the printed concrete filaments and future research should be done on the directional characteristics of the fibres aligned by this extrusion method. Further, Sun et al. [125] showed that the interfacial flaws have a sizable impact on the carbonation depth and permeability of the printed concrete samples. The chloride penetration depth along the layer interfaces was significantly higher than that in the matrix, and the depth of carbonation of the printed specimens was often larger than that of the cast specimen. Additionally, it was observed that there was a steady decline in the depth of carbonation and chloride ion penetration in the gravity direction.

According to Moelich et al. [126], in comparison to traditional cast concrete, 3D printed concrete exhibits a high magnitude and rate of plastic shrinkage (early-age drying-induced shrinkage).

Further to concrete, 3D-printed polymers have been found to host more voids than conventionally moulded polymers. Afshar and Mihut [127] looked at the impact of synergistic UV light and moisture exposure on the mechanical characteristics and microstructure of 3D printed Acrylonitrile–Butadiene–Styrene (ABS) constructions. The study showed that when 3D-printed ABS samples were exposed to extreme climatic conditions without the use of appropriate coating systems, considerable microcracking occurred on the surface of the samples, significantly reducing their mechanical capabilities. Due to the metallic surface's ability to reflect UV rays and provide corrosion protection through surface passivation, the copper coating provided good protection for 3D printed ABS structures against environmental exposures, while uncoated samples dramatically lost their mechanical properties even after brief environmental ageing.

Given all the above studies, and considering the scale of durability studies, one could conclude that the long-term performance of large-scale 3DP structures under aggressive environments could be a challenge and must be studied comprehensively before prescribing the method for remote housing.

In remote areas, similar to human life [128], structures have relatively shorter life [90]. According to a remote housing project manager at the Department of Infrastructure Planning and Logistics (DIPL) of the Northern Territory Government (NTG), the service life of remote dwellings can occasionally be as short as seven years, which is consistent with the range of 4–8 years mentioned in [22]. Besides, aggressive environmental conditions [129,130], poor maintenance, overcrowding (under-resourcing) [29,94,131], domestic violence incidents, and anti-social behaviour, all contribute to the short lifespan of remote homes [132,133]. Each of the aforementioned arguments is accompanied by several circumstances. Environmental and societal factors are the two main categories of reasons why buildings deteriorate in remote communities. High humidity, intense UV exposure, strong winds, cyclones, severe rain, and flooding are all examples of environmental factors. Poor technical skills, reliance on outside service providers, domestic abuse, etc. are examples of social reasons. Reducing external loads on the structures and strengthening the structures are two complementing strategies that could be used to increase the durability of buildings in remote areas. Given the durability challenges of 3D printed concrete structures compared to conventional cast concrete, together with the additional remote social misbehaviour and low maintenance, one could conclude that the long-term structural performance of 3D printed houses in remote locations is the most challenging issue. Case studies are needed to monitor the degradation process of such structures during the life-span of the structure.

5.8. *Design codes and regulations*

The lack of codes/standards on the use of 3D printing in construction is another challenge. The design must adhere to all applicable construction requirements. However, it would be challenging to apply the technology in a way to adhere to all the construction guidelines since there are no established regulations for the use of 3D printing in construction. The existing 3D-printed building structures are only experimental projects because further research is needed to characterise print materials, clarify construction techniques and printing methods, and integrate them with current building code requirements [80]. To date, there have been some efforts being made to include 3D printing in current design regulations. For instance, in China, several businesses are collaborating with the Chinese National Construction Standards Department to change building regulations to incorporate 3D printing [82].

A change in architectural and engineering designs is also necessary to make 3D printing feasible in the building industry. Due to its capacity to produce geometrically complicated and configurable goods, Advanced Manufacturing (AM) will result in a significant change in the design and production process [134]. Moreover, the difference between the material used in AM and the traditional construction materials should be considered in the design process [47]. Nozzles are utilised in 3D printing construction to transfer materials; therefore, the design must include the pumping pressure and the mechanical setup into consideration as well [29]. With this regard, several researchers [45,115,135] studied the effect of nozzle size and shape on the mix extrudability. For example, Shakor et al. [135] evaluated the output of 3D-printed objects made with rectangular and circular nozzles. Flexural strength and consistency of the outcomes were the parameters that were studied. They demonstrated that a square or rectangle-shaped nozzle produces better printing results than a circular one. Perrot et al. [115] came to the same results when looking into how earth-based materials are processed and printed.

Generally, existing architectural systems cannot readily be used in 3D printing exercises since they do not comply with the relevant construction standards, hence a new architectural design system must be developed to meet 3D printing specifications [47]. For instance, the idea of contour crafting, which enables in-situ printing of homes, may be employed for a new architectural method of building design [78].

5.9. Construction setup and planning

Since they don't offer a regulated environment, most current construction site layouts present difficulties for implementing AM. The equipment's capacity to adapt to various applications with various access levels, geometries, and underlying materials also poses issues, as does the transportation and setup of the equipment at the construction site [16]. The transportation of the printer on-site can be challenging and costly due to the size of the printer [77]. This issue will be more significant when it comes to remote construction. To achieve the optimum results, the existing on-site fabrication AM systems still need a specific type of enclosure or particular environmental requirements to be met [16]. To provide continuous feed to the nozzle, material preparation and delivery system are also required [71]. With all the challenges of setting up an AM construction site, Bock notes that robot systems' capabilities have evolved over time and that they can function in "comparably unstructured environments" [136] in near future. This demonstrates that setting up a building site will become simpler over time and with more research.

Construction scheduling demands new knowledge and methods as a result of the use of 3D printing in construction projects. The new construction plan will need to use both machine scheduling and conventional scheduling methods. Due to the directional dependency's effect on print strategy, machine scheduling is complicated. Additionally, the majority of the printing activities will be continuous, as opposed to the discrete activities that typically make up building schedules [57].

5.10. Training needed for construction workers

When building with a 3D printer, there is less demand for manpower. Technology encroaches on the tasks traditionally done by humans on construction sites [137]. Although the new technologies will reduce opportunities for many people working onsite, it may be advantageous in terms of labour costs. Reduced labour demand, according to some scholars, may cause political instability in particular economies [118].

The construction sector is suffered from labour-intensive and high-skill traditional procedures, making the adoption of automation technologies difficult [65]. Building employees will need new skills to incorporate the use of 3D printing in construction. The installation, use, management, and upkeep of 3D printers are among these new skills. On a typical construction site, these new abilities, which are crucial to guarantee a successful project, are not easily accessible [80].

Training for 3D printing construction becomes more challenging when it comes to remote communities where literacy and numeracy are big challenges [138] and in many cases, English is not the first language [139,140]. Furthermore, the lack of experience with the technology of construction will mean the uptake of new technology in local engagement will be slow.

On the other hand, holding construction training in communities would encourage young people to stay in their communities. The irregular nature of construction projects in communities usually does not make enough job security for young people to stay in their home community while upskilling them opens doors to opportunities in neighbour communities [141]. With the provision of the equipment to print such houses, the local team would work around the region to those communities that they have access to, or the equipment could be shared with further training of another community's members.

6. Completed 3D-printed construction in remote locations

This section is devoted to a brief presentation of some finished projects. This includes the analysis of the steps to choose a 3D-printed construction as construction method in remote locations.

A portable gantry-style printer that prints homes and other structures out of a unique concrete mixture was developed by ICON, an Austin-based construction technologies company [142]. ICON's first project was a 32.5 m^2 proof-of-concept home printed on-site in Austin, Texas, in March 2018. The home was permitted, built to International Building Code standards, and completed in approximately 47 h of total printing time [142].

ICON then built a Welcome Center at Community First! Village in Austin, TX for the non-profit organization, Mobile Loaves & Fishes. Soon after, ICON broke ground on a series of 3D printed homes in 2019 in Nacajuca, Mexico, which is depicted in Fig. 7, after 18 months of design and technology development. Each 46.5 m^2, two-bedroom house was built for housing non-profit New Story and took about 24-h of print time across several days, despite difficulties with erratic power, strong rain, and localised floods [142]. The families selected to receive one of the ten 3D-printed homes by New Story had a median monthly family income of \$76.50 and were previously living in unsafe, makeshift shelters [142]. In terms of structural design, process efficiency, labour, environmental impact, and cost, this application showed the potential of 3D printing for remote housing. The harsh weather was found the largest obstacle to the practicality of 3D-printed construction in that exercise.

Another example is the Automated Construction of Expeditionary Structures (ACES) programme was established by the United States Army Corps of Engineers Engineer Research and Development Centre -Construction Engineering Research Laboratory (ERDC-CERL) in 2015 to create dependable, user-friendly 3D printing technology capable of producing specially designed military expeditionary structures on demand, in the field, using locally accessible materials [144]. The ACES initiative aimed to use less material, build stronger, longer-lasting structures, use less labour, and reduce the logistical and supply requirements of construction. The program's current emphasis was on using the 3D-printed building in expeditionary settings. The programme used the ACES Lite prototype gantry-style 3D printing machine, which was created and constructed as part of a joint research and development project between Caterpillar and ERDC-CERL. The printer was made to be easily assembled, extremely transportable, and operated by a small number of people. A 3 m^2 military entry check post, two 48 m^2 concrete barracks huts (B-huts), a 10 m 3D-printed concrete bridge, and a 7 m^2 military defensive combat position were just a few of the prints the ACES team has done since May 2016. The bridge was the first of its sort printed in a field environment in the US, while B-Hut 1 was the first full-scale, 3D-printed concrete construction in the country [145,146]. The emphasis throughout the printing of the second barracks hut was efficiency: B-Hut 2 was produced in 14 h of print time and 31.2 h of elapsed time over the period of five days. [147,148]. Fig. 8 shows the printing process and the completed military structure. The U.S. military is getting closer to having reliable, deployable building technologies thanks to each of these operations, which highlighted the printers' capacity to use locally obtained materials and function in uncontrolled climatic circumstances [149].

The tiny Ashen Cabin is another successful 3D-printed building. The building is located off the grid in upstate New York built in 2014 and was designed by a group of Cornell University students in collaboration with the Ithaca studio (Fig. 9). The cottage was built as part of a joint initiative that combined 3D printing and EAB-infested ash wood as a small-scale study of sustainable construction. HANNAH turns "waste

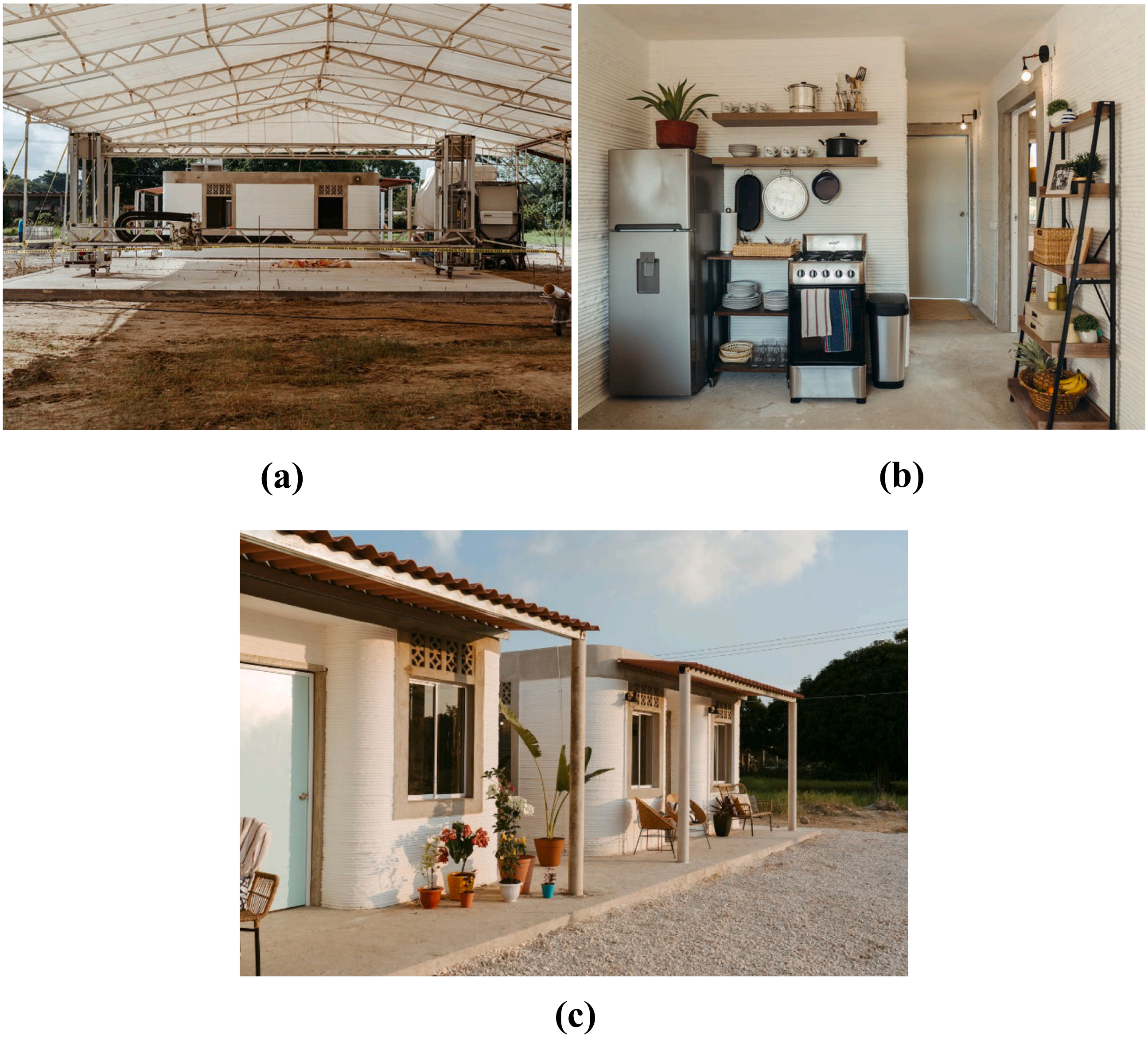


Fig. 7. ICON buildings in Tabasco, Mexico: (a) Printing process, (b) inside view of the completed 3D printed home, and (c) outside view of the completed 3D printed home [143]. Image courtesy of the ICON. Photo Credit: Joshua Perez for New Story.

wood" infested with the Emerald Ash Borer into a readily available, reasonably priced, and environmentally friendly building material by utilising high-precision 3D robotic fabrication technologies. Digital design and fabrication technologies are key to the creation of this architectural prototype, enabling radically novel construction techniques, tectonic articulations, and material strategies. Concrete was also utilised to 3D print a one-of-a-kind seating platform. The ash logs were uneven, and a robotic arm with a band saw attachment turned them into curving boards of various thicknesses. The four black plywood-framed windows and other architectural details, such as surfaces and shelving within, are all defined by the wavy timber panels that cover Ashen Cabin's outside and interior [151].

One more example of a 3D printing project is 14Trees, done in Malawi and Kenya (Fig. 10). The printer used in this project can construct a 3D-printed house in just 12 h for less than $10,000. When compared to a regular house-building project, its construction technique lowers CO_2 emissions by 70%. It has also created a website that encourages people in the African diaspora to buy a "house back home." In addition, 14Trees just finished building its first 3D-printed school in Malawi.

The introduction of 14Trees' top-notch, cutting-edge technology will have a significant positive developmental influence on Malawi and the surrounding area, according to Tenbite Ermias, managing director of CDC Africa [152].

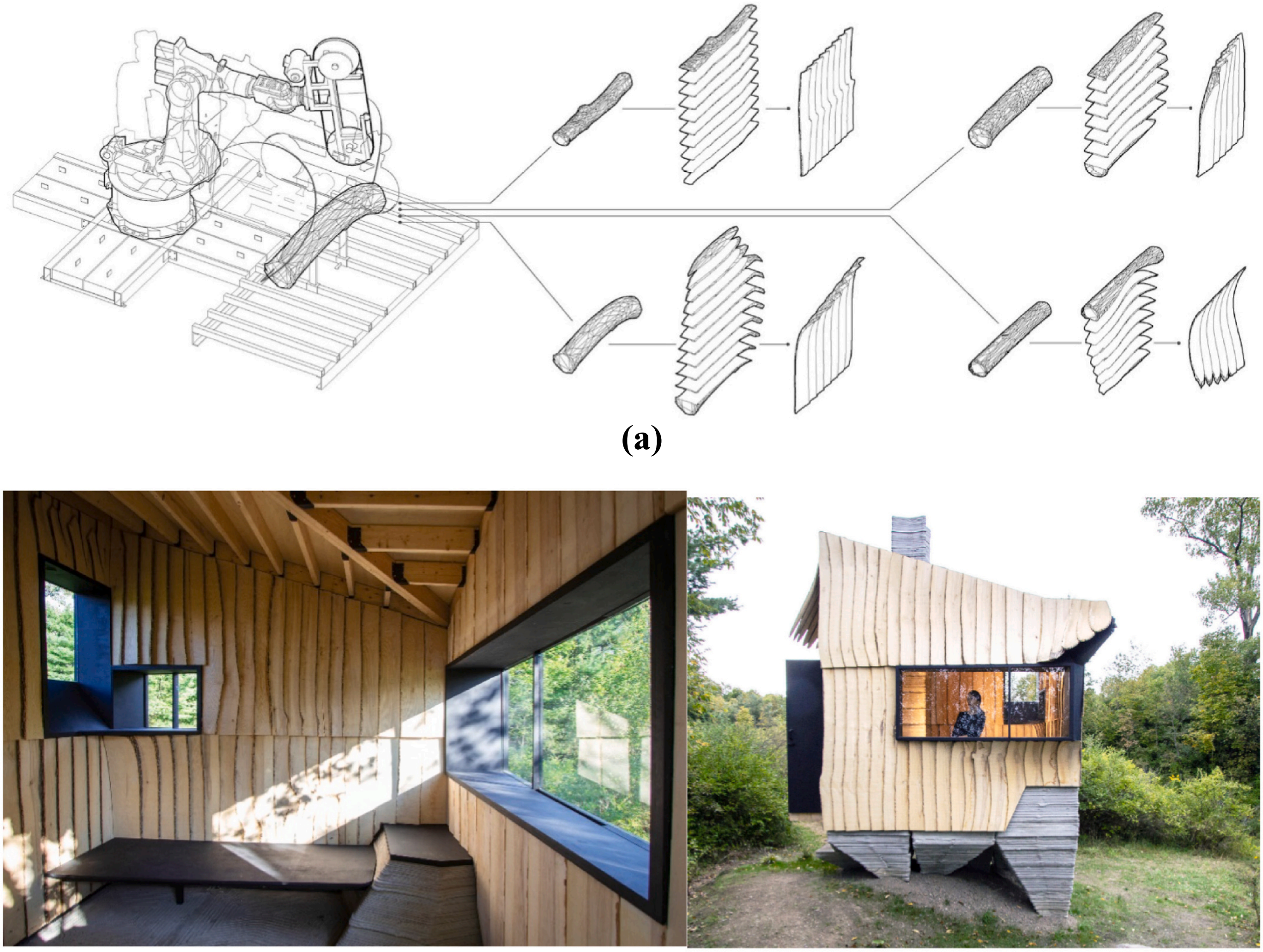
7. Conclusion and recommendations and limitations

The paper provides a thorough discussion of the literature on 3D printing and its advantages and limitations in remote housing. It fills the gap in previous review papers of a similar nature and provides a more comprehensive look at the managerial and technological issues of construction 3DP when it comes to remote areas. From the literature review and the discussions, the following key points, recommendations and limitations could be summarised:

- 3D printing has the potential to overcome various challenges in the remote construction sector. It could become more effective and sustainable with the help of Industry 4.0 developments [153]. However, there are still several uncertainties, which must be studied and addressed before the wide use of the technology.


(a) (b)

Fig. 8. ACES military project: (a) Printing process, and (b) completed structure [18,150] (Images have been declared public information by Marine Corps Website of US government and is not subject to copyright protection in the United States).


(a)

(b) (c)

Fig. 9. HANNAH Ashen Cabin project: (a) printing process (b) inside view of the completed building, and (c) outside view of the completed building [151]. Image courtesy of the HANNAH.

Fig. 10. 14Trees project: (a) printing process (b) completed building [152]. Image courtesy of the 14Trees.

- The use of 3D printing in remote housing is still in its infancy and feasibility stage. Despite the significant advancements in technology as stated in the literature it still has a way to go before justifying its widespread adoption. Numerous areas of research are still being done, particularly those involving robotics and materials.
- Trade-offs between several factors, including materials, structural design, process efficiency, logistics, labour, environmental impact, and cost, must be taken into account to determine whether or not 3D printing is practical and preferred in remote environments. However, since the variables are all interconnected, it is uncommon for a single building technique to optimise all these areas. Therefore, it can be concluded that the efficiency of each construction method in remote housing could vary case by case. Decision-makers will need to take into account the trade-offs between traditional and 3D-printed construction technologies as well as the expected effects of their choice on the local society and economy as 3D-printed construction continues to develop and become more competitive.
- 3D printing needs special material qualities. Such requirement makes it very challenging when the project is located in remote areas. 3DP would be a cost-effective solution if the local materials meet the printability, buildability and robustness requirements. However, the feasibility and cost efficiency of the project must be evaluated when the local materials do not meet such specifications.
- In remote locations sometimes it is possible that a location has great strategic value as a hub for logistics and that intergovernmental relations, such as time and labour make using conventional construction methods impossible. In such circumstances, 3DP could be considered a promising solution to overcome such a challenge.
- Storing printers in a few remote hubs and deploying them to the communities in a hub's catchment area could be a solution for issues associated with the transportation of the printers.
- It is crucial to keep in mind that the cost comparison between the 3Dprinting method and other conventional construction methods provided in this review paper is only a rough approximation, given that the numerous factors, such as the complexity and technology level of the printer, materials type, availability, and transportation, etc. significantly affect the total project cost. Therefore, the lack of a comprehensive life cycle cost assessment (LCCA) must be mentioned as one of the major limitations in the field of concrete 3D printing in remote areas.
- Since using concrete 3D printing in construction applications and particularly in remote locations is a very recent activity, the available data on the printed houses' long-term structural performance under different loading and environmental conditions is very limited. Since the lifespan and maintenance of houses in remote locations are of great importance, the lack of data on the durability performance of 3D-printed houses is a significant limitation in this area and must be addressed in future studies.
- The lack of design guidelines for concrete 3D printed houses, especially in an aggressive environment, such as cyclonic areas of Australia's Northern Territory, should be mentioned as another limitation. More experimental data on the structural performance of 3D printed structures in different loading and environmental conditions are needed before the mass production of 3D printed houses for remote locations.

In summary, given all the benefits and limitations of concrete 3D printing for remote housing, it can be concluded that before finalising the construction method, the pros and cons of using 3D printing must be evaluated case by case taking into account several factors ranging from the printing technology, materials quality and availability to the logistics, labour, and community engagement.

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

No data was used for the research described in the article.

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