ARCTIC
VOL. 77, NO. 3 (SEPTEMBER 2024) P. 261–271
https://doi.org/10.14430/arctic80896

3D Additive Construction: A Potential Solution for the Housing Crisis in the North

E. Erhan Dikel[1,2] and Lauren Arbuckle[1]

(*Received 15 September 2023; accepted in revised form 17 June 2024*)

ABSTRACT. Northern communities in Canada are facing a severe housing crisis. Living conditions, including the current state of the wood-frame houses, are leading to health complications and other severe problems. Additive construction (AC) is an emerging digital construction technology that could help with this desperate housing situation in the North. AC presents potential advantages that apply to the North, such as significant reduction of labour, construction, and material costs, as well as reduction of construction waste. Fewer skilled workers required to travel from the South and less material required to print houses in a short time will help decrease costs related to construction. As with any new technology, there are potential challenges that should be addressed, such as its economic, social, and environmental impacts; method of transportation; and performance in a cold climate. In addition to that, when designing and printing houses in the North, it is important to consider the social and cultural factors that will influence successful market adoption.

Keywords: 3D printing; 3D printed construction; 3D construction printing; 3D additive construction; digital construction; affordable housing; alternative construction technologies

RÉSUMÉ. Les collectivités nordiques du Canada font face à une grave crise du logement. Les conditions de vie de même que l'état actuel des maisons à ossature en bois posent des problèmes de santé et d'autres difficultés majeures. La construction imprimée en 3D (AC) est une technologie de construction numérique émergente qui pourrait contribuer à améliorer la situation désespérée du logement dans le Nord. La technologie AC offre des perspectives prometteuses pour le Nord, notamment une réduction significative de la main-d'œuvre requise, des coûts de construction et des déchets de construction. De plus, avec moins de travailleurs qui doivent se déplacer du sud vers le nord et une quantité moindre de matériaux nécessaires pour imprimer rapidement des habitations, cette innovation contribuera également à maîtriser les coûts de la construction. Tout comme pour toute nouvelle technologie, l'impression de maisons soulève des défis, tels que les répercussions économiques, sociales et environnementales de cette méthode de construction, l'impact sur le transport et l'efficacité des habitations dans les climats froids. De plus, pour que cette technologie soit adoptée sur le marché dans le Nord, il est important de tenir compte des facteurs socioculturels susceptibles d'influencer son succès.

Mots-clés : impression en 3D; construction imprimée en 3D; impression de construction en 3D; construction additive, logement abordable; technologies de construction de rechange

Traduit pour la revue *Arctic* par Nicole Giguère.

INTRODUCTION

The housing situation in the North has reached a crisis level. There are four major problems: a severe housing shortage, overcrowding, hidden homelessness due to long waiting lists, and poor housing quality (Coates, 2018). Mumilaaq Qaqqaq (2021), a former MP for Nunavut, has also documented the unacceptable living conditions in the North with real life examples.

The current building practice in the North uses techniques and materials optimized for the relatively mild and predictable climate of the South. Materials such as wood and plasterboard are expensive to transport, perform poorly in the North, and emit large amounts of CO_2 to manufacture and process. In addition, research reveals respiratory illnesses caused by moulded plasterboard and wood frame, another proof that conventional construction techniques are not working in the North (Kovesi et al., 2022) (Fig. 1).

In the last few decades, a new construction technology has started to emerge that has the potential to change the way we build our communities: additive construction (AC). Although its origin dates back to the 1940s, in the past ten years we have witnessed a rapid development of the AC technology, which has significantly increased the number of 3D-printed structures (Bos et al., 2016; Urschel, 2017).

In principle, AC is a computer-controlled process that sequentially layers materials to create three-dimensional shapes and structures. The technology is described as an "additive, layer-by-layer construction method with the potential to reduce material consumption, optimize design, decrease construction time, lower labour requirements,

[1] National Research Council Canada, 1200 Montreal Road, M-24, Ottawa, Ontario K1A 0R6, Canada
[2] Corresponding author: erhan.dikel@nrc-cnrc.gc.ca

FIG. 1. House in disrepair in the North constructed with conventional materials. Credit: Karen Pauls, CBC. https://www.rcinet.ca/en/2019/10/21/new-un-report-scalds-canada-for-indigenous-housing-conditions/.

minimize logistical demand, improve sustainability, and reduce costs as compared to conventional construction" (Schuldt et al., 2021:1) (Fig. 2).

AC technology is no longer experimental, and nowadays families are living in fully functional printed houses. Canada's first 3D-printed, multi-unit houses were built in 2022 (Fig. 3). Located in Leamington, Ontario, four houses of 52 m^2 (560 ft^2) each were printed in 200 hours with a total budget of $600,000 (Nidus3D, 2022) (Fig.3).

AC technology is a promising candidate to solve the housing crisis in the North. In addition, "using funds currently allocated for standard house construction, the transition to 3D-printed homes could contribute to a more rapid elimination of the shortage of housing in the North" (Coates, 2018:10). Sustainable, healthy, affordable, and net-zero energy-ready houses could be printed year-round by using mostly local materials, without relying heavily on building materials and skilled workers brought in from the South. The potential of AC to reduce labour, material, supply, and construction costs is seen as a major advantage, however, implementing this technology in the North requires more research. This brief article aims to introduce the AC technology and discuss its advantages and potential application in the North.

WHAT IS 3D PRINTED CONSTRUCTION?

Before comparing AC with conventional construction techniques, it is critical to understand how the technology works. Buchanan and Gardner (2019:333) describe AC as an automatic process as follows: "These methods all broadly follow the same workflow process: firstly, a 3D CAD model is created; this is then sliced into a series of building layers; this information is then sent to the processing machine, defining the location of the building head; and finally, the part is built up layer-by-layer."

This process can be highly customized to focus on aspects such as design optimization, structural integrity, specific resiliencies, and reduced material usage. AC can form the majority of a structure entirely from a 3D model, using materials such as concrete, foams, and earth matter. This process can be performed either on-site or components can be prefabricated off-site and transported to the building location.

COMPARING AC WITH CONVENTIONAL CONSTRUCTION

Maturity

Conventional construction uses a well-established protocol that is limited only by human factors, materials, and timelines. It has a large standing workforce, stringent guidelines, public acceptance, and well-tested techniques. AC, on the other hand, is a new technology characterized by technological advancement, geometric optimization, lower costs, reduced labour, improved logistics, and condensed timelines (Sheikh and Sharma, 2020; Schuldt et al., 2021). This new technology also has the potential to increase productivity through shorter timelines, smaller

FIG. 2. 3D printer gantry system printing a wall section. Source: https://weprinthomes.com/.

supply chains, and technological innovations such as automation, recycling of material waste, less reliance on heavy machinery, and efficient use of materials.

Digital and Flexible

Conventional construction is a field with low customization and is often viewed as a low-tech industry with low levels of innovation (Dubois and Gadde, 2000; Harty, 2008). However, unlike conventional methods, AC generates a construct directly from a digital file and is capable of customization to a great degree without incurring additional costs (Hague et al., 2003; Gao et al., 2015; Buchanan and Gardner, 2019). Designs can be made and uploaded remotely. The complexity of a 3D building becomes irrelevant once it is sliced into two-dimensional layers, because the printer can generate the more complex shapes of each layer without any appreciable changes in material consumption or timeline. 3D models can also be more effectively communicated and edited than conventional blueprints or design sketches (Camba et al., 2014). Whether the design is simple or highly intricate, cost is always dependent on the technology employed, the materials used, and the size of the building being constructed.

Environmental Impact

Conventional construction is notorious for its negative environmental impact (Wu et al., 2016; Camacho et al., 2018; Schutter et al., 2018; Han et al., 2021). Current construction techniques are responsible for 40% of the world's material and energy use, as well as 38% of greenhouse gas emissions (Dixit, 2019a; 2019b; Schuldt et al., 2021). Overall, AC has the potential to reduce the environmental impact of construction by optimizing material consumption, recycling wasted materials, and eventually using ecofriendly materials. Estimates place the overall reduction of the environmental impact at 50% (Gebler, 2014; Schutter et al., 2018), reduction of material consumption at 40% (Verhoef et al., 2018), and reduction of waste at 30% (Perkins and Skitmore, 2015). However, in the current state of the technology, whether or not AC uses less energy than conventional construction methods depends on

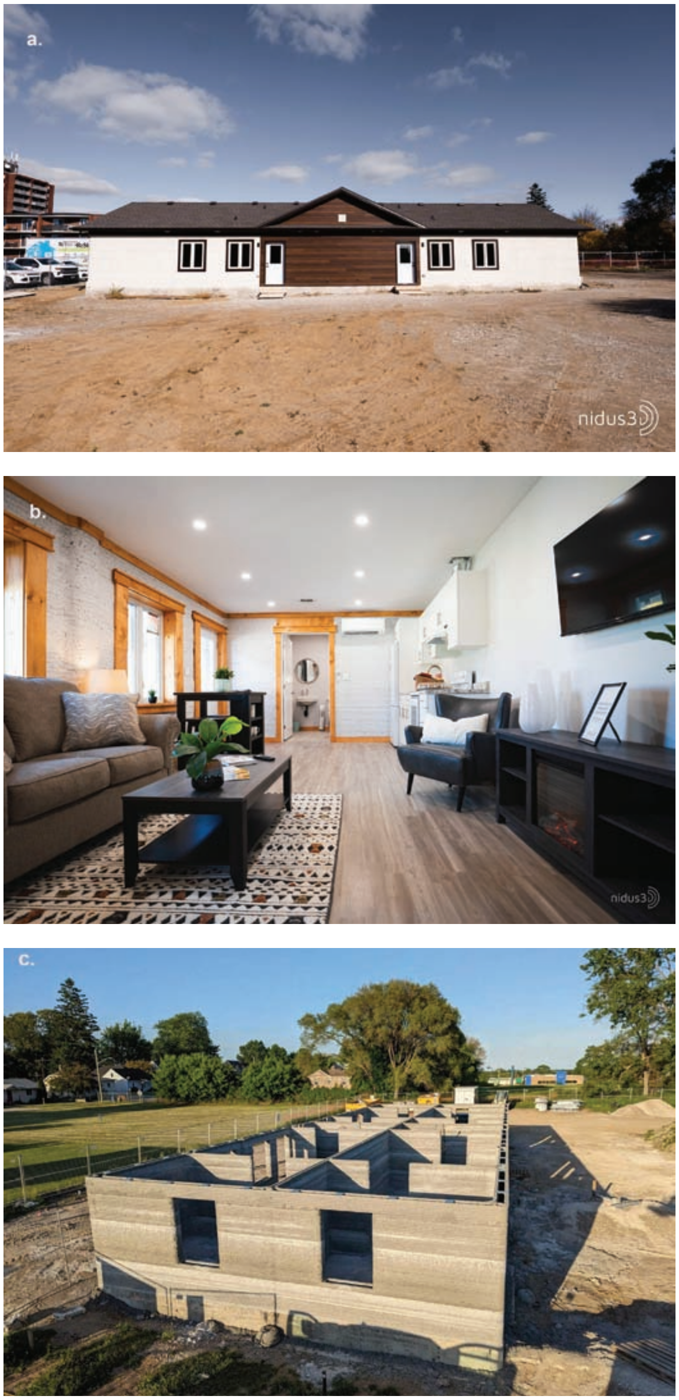

FIG. 3. Views of Canada's and North America's first 3D printed MURBs (multi-unit residential buildings). Source: https://nidus3d.com.

the printer system and the materials used. Some literature reports that AC uses less energy, whereas others point to higher energy use than conventional methods.

Cost

One cost benefit of AC is the elimination of the need for formwork (Nematollahi et al., 2017). Given that scaffolding, concrete moulds, and their associated labour requirements typically account for 35%–60% of the total construction cost, AC can generate substantial monetary savings (Bos et al., 2016; Schutter et al., 2018). Eliminating the need for formwork not only reduces construction waste, but also reduces both materials and labour, cutting out a time-consuming step in the construction process (Ghaffar et al., 2018; Schuldt et al., 2021).

Restrictions

Conventional construction, with its well-established protocols, technologies, techniques, and materials, has no significant restrictions. While 3D printing claims a number of advantages compared to conventional construction methods, it also has limitations and risks that require special attention before this emerging technology can be adopted (Wu et al., 2016). The current restrictions of AC are mostly linked to system and technological limitations. For example, the ability to print only one material type per machine, and a smaller pool of usable materials than those available in conventional construction.

Each material has benefits and weaknesses that must be kept in mind when allowing for the inclusion of other building systems, insulation, reinforcement, or surface finishing.

The technique is based on the extrusion of a material directly on the previous layers. Therefore, overhangs and structures such as ceilings, multiple storeys, and roofs require clever workarounds and additional labour. Such issues add to the front-end planning of construction with 3D printers. However, as the technology matures, more improvements and viable techniques may emerge with increasing rapidity.

Although surfaces can be treated to achieve any kind of finish, the printing process creates visible layers and uneven wall surfaces that may require smoothing, based on preferences.

The equipment required for AC runs on electricity. This can potentially add extra demand on the diesel-generated, isolated network of the northern communities. Therefore, further studies are needed to estimate and analyze the power consumption of this technology and find ways to design components that are as energy efficient as possible.

It is important to note that, with the correct materials and skilled labourers, conventional construction can generate any components necessary to build a complete and livable structure. This is unlike the current AC technology, which often can generate only structural components such as walls, floors, and supporting structures, but not overhanging components (such as roofs, ceilings, and multiple floors). What AC does achieve is the automated completion of the bulk of construction using a single material, such that the major resource-demanding and time-consuming aspects of construction are completed in a faster and more cost-effective manner. Therefore, while the two technologies look like rivals, AC, in its current state, still relies on conventional methods to create some parts of a structure and its subsystems.

NORTHERN SPECIFIC POTENTIAL ADVANTAGES

Reduced Labour Cost

Currently, construction in the North is expensive and challenging because it is far away from major urban or industrial zones and depends mostly on seasonal labour travelling from the South. Reducing reliance on imported, seasonal skilled workers is one of the main benefits of AC. Automating the construction industry through AC can help mitigate labour shortages at remote locations because this technology requires fewer workers and is less vulnerable to a lack of skilled labour (Perkins and Skitmore, 2015). This decrease in labour requirements also simplifies transportation logistics, because fewer workers need to travel to the remote location and commute to and from the jobsite each day (Rouhana et al., 2014). In addition to logistics, other cost benefits related to labour include a reduction in overhead costs because less supervision is required, improvement in productivity, and fewer errors (Rouhana et al., 2014; García de Soto et al., 2018).

Labour costs in conventional construction are often higher than material costs. In AC, these proportions are reversed, and the labour costs are less than half of the material costs (Kreiger et al., 2019; Smith, 2012). This correlation plays an important role in remote locations such as the North.

Reduced Construction Cost

Reduction of costs related to human involvement is not limited only to workers in the North. AC has been referred to as an emerging technology that aims to reduce construction industry costs through the automatic construction of a building's components directly from a digital file without human intervention (Ghaffar et al., 2018; El-Sayegh et al., 2020).

As Schuldt et al. (2021) stated in their report on AC in remote environments, the costs of construction planning and design are expected to decrease because of advancements in 3D modelling, building information modelling, and other technologies. In fact, one study compared different methods of constructing a structural wall and found that AC is 10%–25% cheaper than the cost of building with concrete masonry units, and 25%–37% cheaper than the cost of cast-in-place construction (Kreiger et al., 2019). This effect would be more pronounced in remote environments (Schuldt et al., 2021).

Reduced Material and Supply Cost

Another challenge for the current construction sector in the North is the high material cost related to the long and challenging supply chain. AC potentially simplifies construction logistics and management through a shorter supply chain and a lower equipment and material transportation time, both of which increase productivity (Sakin and Kiroglu, 2017; Schuldt et al., 2021).

AC has the potential to shrink the supply chain by printing objects on demand, thus eliminating the lead time for materials that need expedited delivery. This process increases productivity, which otherwise would have been affected by late deliveries (Camacho et al., 2018). In addition, AC can potentially use locally sourced or in situ materials when available and accessible. Using local materials reduces or even eliminates the transportation of material transportation logistics to remote, hard-to-reach locations and reduces the need to store and maintain extensive material inventories (Ford and Despeisse, 2016). Using raw earth materials also eliminates the lead time for obtaining materials, thereby shortening the supply chain. As Schuldt et al. (2021) indicate, material costs can also be reduced by optimizing the design to avoid over-engineering, thus reducing material waste, leveraging the use of locally sourced or recycled resources, and minimizing the need for material transportation and storage.

Waste

Waste management is a very serious problem all across the North, and construction is considered a major contributing factor (Oceans North, 2021). Regardless of the material extruded from the 3D printer, AC technology uses only the amount of material needed, which is placed with a high degree of precision only where necessary. This eliminates both formwork and waste (Ford and Despeisse, 2016; Verhoef et al., 2018). Additionally, properly planned architectural layouts and material selection provide the opportunity to reduce overdesigning and material waste. This optimizes material usage and decreases wastefulness, while still allowing for a high degree of design freedom. Application of these principles makes building highly individualized yet efficient structures a possibility (Agustí-Juan and Habert, 2017).

NORTHERN SPECIFIC POTENTIAL CHALLENGES

Economic Impact

The construction industry plays an important role in the local economy in the North (Labonnote et al., 2016). Multiple sectors benefit from the temporary labour force that comes to the North during the construction season; workers need accommodation, food, and other living provisions during their stay. Some authors have pointed out that the reduced need for labour could be politically destabilizing for some economies (Campbell et al., 2011). This potential impact of the AC technology on the local economy could be mitigated by using the local labour and supply chains.

Social Impact

The current construction industry relies on high-skill, labour-intensive conventional processes, not conducive to adaptation of automation technologies (Khoshnevis et al., 2016; El-Sayegh et al., 2020). Since most of the 3D printing process is highly automated, the workforce required in the construction process can be significantly reduced (Wu et al., 2016). The social impact of AC is highlighted by El-Sayegh et al. (2020:34) as having a "negative effect on the existing construction workforce and creating social problems in some communities that rely on construction activities." It is believed that "3D printing will reduce the need for large numbers of construction workers and although this is considered a benefit, as it reduces labour cost, it is also a disadvantage to those workers whose jobs will be at risk" (El-Sayegh et al., 2020:34). While it is clear that the use of 3D printing technology in construction lowers the need for traditional construction labour, it simultaneously presents new opportunities for specialized jobs with different skill sets such as installation, operation, control, and maintenance of the 3D printers (Kreiger et al., 2015; Camacho et al., 2018; El-Sayegh et al., 2020). The AC technology also has the potential to change the labour structure, supporting gender equity and a safer working environment (Ghaffar et al., 2018).

Social and Cultural Factors

The introduction of a novel technology has the potential to negatively affect the cultural structure of an isolated community (Coates, 2018), which must be recognized and mitigated. Regardless of the type of technology to be introduced to the North, potential cultural impacts must be studied, preferably in collaboration with the people who live there and with sociologists who are specialized in Northern communities.

It is important to acknowledge social and cultural traditions when building houses in Northern communities. For example, sufficient room should be included in any structure that allows family members and company to visit (BC Housing, 2018; Native Women's Association of Canada, 2023). Living with relatives in addition to immediate family members is a widespread cultural tradition in the North. Building houses that have room for each family member to have their own space, while being able to interact with one another is important. As well, since it is common for Elders to live with their families, ensuring that houses are accessible is necessary. Places in the home where gatherings occur, such as the kitchen and living room, should be large enough to accommodate visitors. Incorporating circular structures into areas of the house where ceremonies occur is helpful for promoting community. Since hosting gatherings is common, it is important to include rooms in the house where children can have their own space. This is beneficial for when children need a quiet area to rest. Lastly, having a garden area near or in the house (e.g., LED-powered greenhouses) can provide a place for people to grow food. Incorporating these factors will help to strengthen relationships between family members and members of the community, while providing spaces to engage in traditional activities (Bowra and Mashford-Pringle, 2021).

From an architectural point of view, by using AC, it is possible to print creative architectural forms that align well with the aesthetic preferences of local cultural norms and heritage. However, tailoring the architectural design of the printed Northern houses to the needs, lifestyle, and social habits of Northerners is equally essential. This is critical for the acceptance of the novel houses. The Penn State team followed that principle and designed their house model to be highly customizable for the needs of the families (Penn State, 2024). They prepared a questionnaire to collect feedback from the residents of a site in Alaska on how they live and asked about their expectations for the homes. They created a "rule-based design system," which generates "diverse housing solutions that take a family's needs into account by offering different options for kitchen sizes, bathroom and room numbers, and relative locations" (Penn State, 2024:paragraph 19). Figures 4a and 4b show the resulting customizable house design.

The Penn State team is definitely moving in the right direction by learning what users need and by designing the 3D-printed houses to address those needs. However, the house they are planning to print cannot be changed once completed; therefore, the house cannot be adapted to respond to a family's changing needs. Modular construction might be a better alternative for a more flexible 3D-printed

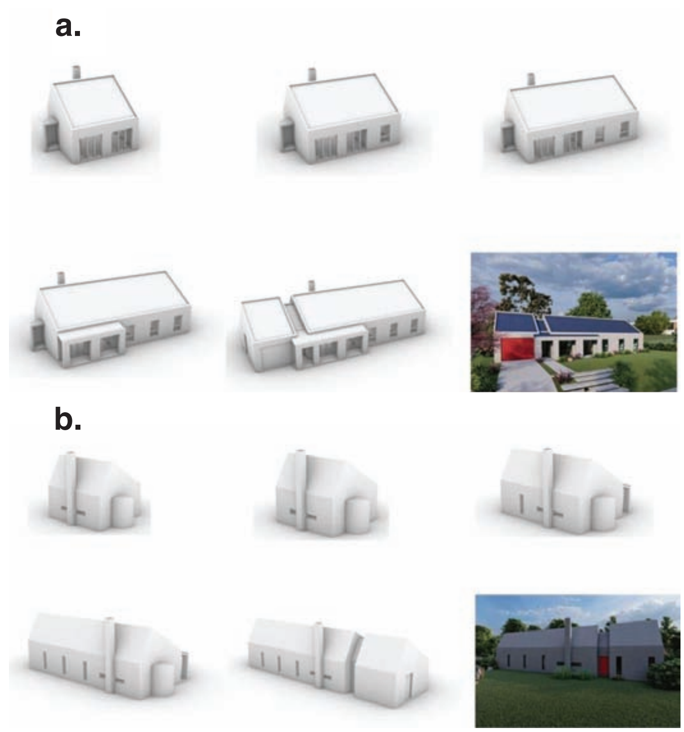

FIG. 4. The customizable house design (front 4a and back 4b) developed by Penn State University for a project in Alaska.

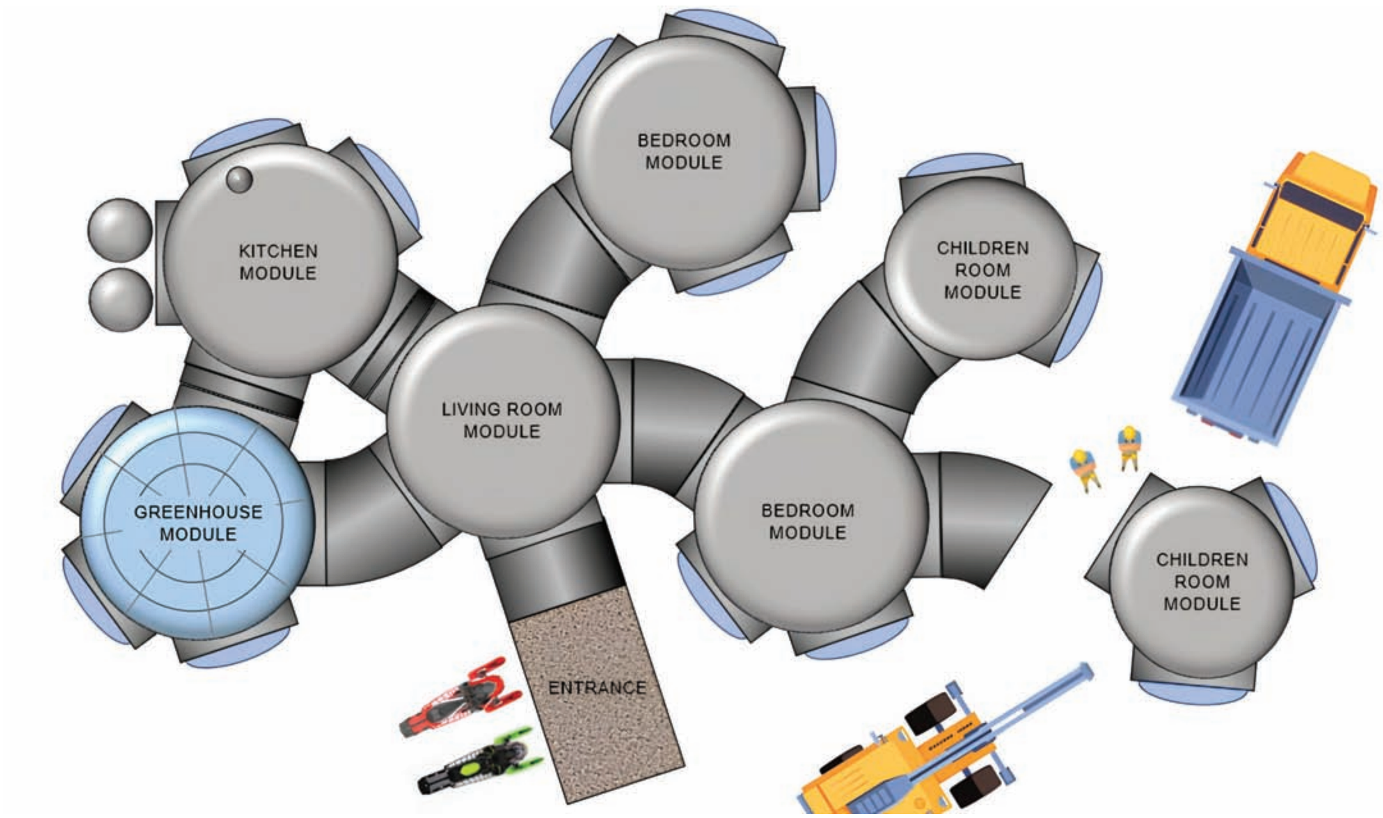

FIG. 5. A modular housing concept for the North. This concept was developed by the authors.

house design. Figure 5 shows a conceptual design of a modular house. Each module has a specific design, according to its function (e.g., the kitchen module has extra ventilation and propane tank access, the greenhouse module has more windows, to promote vegetable growth in the summer). In the specific scenario displayed in Figure 5, an extended family grows to include a new member; additive construction allows the addition of a new room module to the home. Ideally, these modules would be printed off-site in a large printing plant, protected from weather and the elements, so printing can be done continuously regardless of the weather (Fig. 5).

Environmental Impact

The northern environment has a very delicate balance, and any new technology introduced in the North must preserve this balance. In AC, three major components should be carefully designed and planned: the 3D printer, the extruded material, and the transportation of the technology to the North.

3D Printer: The printing process itself can lower the environmental impact because printers are capable of being completely electric (Khoshnevis, 2004). 3D printers can either connect to the local power grid or run off generator power in remote locations. One study found that the electricity demand during printer operations accounted for only 2% of the overall life-cycle emissions and environmental impact of a 3D-printed wall (Schutter et al., 2018). The environmental impact of the printing process itself is negligible in comparison to the environmental impact of the material's manufacturing process (Agustí-Juan and Habert, 2017; Verhoef et al., 2018; Schuldt et al., 2021). However, considering that the current method of electricity generation in the North relies on diesel generators, 3D printers should be designed to be as energy efficient as possible to reduce the additional demand to the already overwhelmed and isolated grid.

Extruded Material: The material used in AC is important and it defines whether the technology is environment friendly or not. Today's technology mostly uses concrete. Considering that the concrete industry is responsible for 8% of global CO_2 emissions (Ellis et al., 2020), using concrete in 3D printing would cancel out the other positive impacts of the technology. In order to mitigate the environmental impact of the current AC construction materials, it would be ideal to switch from using highly industrialized materials known to have detrimental environmental impacts and focus instead on developing renewable extrusion materials, such as geopolymers (Liiv et al., 2018; Bong et al., 2019; Panda et al., 2019; Schuldt et al., 2021). Such materials, currently in the design stage, aim to be more environmentally friendly, produce fewer emissions, and have less impact on the worldwide material shortage. Materials that are normally waste, such as waste from the demolition of buildings or recyclable waste from factories, could also potentially be used (Howe et al., 2013; Khoshnevis et al., 2013; Howe et al., 2014; Kading and

Straub, 2015; Mueller et al., 2016; Roman et al., 2016, 2017; Prater et al., 2018; Studios, 2018).

Transportation of the Technology: 3D printing can already be used in certain specialized situations, such as remote locations and disaster sites (El-Sayegh et al., 2020; Schuldt et al., 2021), because of the technology's lower labour needs, simplified logistics, and reduced material and energy use. Printers require far less equipment than traditional construction and are easier to transport and set up. Furthermore, 3D-printed components are lighter and therefore easier to transport (Ma et al., 2018; Hensley, 2021). AC also decreases the transportation impact, fuel consumption, and associated emissions of construction by reducing, or potentially eliminating, the need for diesel-powered heavy construction equipment and for commuting workers to the job site (Smith, 2012; Perkins and Skitmore, 2015). However, if not planned carefully, the transportation cost of the printer to the site can be difficult and expensive because of its size (Maskuriy et al., 2019; Schuldt et al., 2021).

Performance in Sub-Zero Temperatures

One of the most apparent challenges for construction in the North is the extreme cold weather. Similar to conventional construction, on-site 3D printing is also weather dependent (Lim et al., 2012). Although some printers have been shown to operate in −25°C (Demyanov and Popov, 2019), which could potentially extend the length of the productive season for home building, in general AC printers need a controlled environment to operate properly (Camacho et al., 2018)—and in most cases, these conditions are not sub-zero temperatures. Most construction sites in the North would be challenging for AC because of inconsistent environmental factors such as precipitation, temperature or humidity, dust and debris, and variable lighting conditions (Kazemian et al., 2019). On the other hand, assuming the house design is modular, printing individual parts off-site in a controlled environment, and later transporting the parts to the site for assembly would allow continuous printing of building parts. Demonstrating such a potential as innovation progresses will increase the possibility of using robotic systems in challenging environments (Rieuf et al., 2017).

CONCLUSION

The severe housing crisis in the North could be alleviated by using 3D printing in construction, as this technology decreases the need for labour, logistics, and cost while providing a high degree of customization. 3D printing can generate affordable homes through specialized construction, Northern communities can be trained to perform. Specially engineered materials and prospective designs can be weather resistant, safe, and durable, and be customized to reflect local cultural needs.

At this writing, AC technology is beyond the experimental phase and is regarded as a ready-to-use technology. However, unique and large-scale projects still require trial data and custom-made materials and printers. The technology is still relatively young and has a wide range of opportunities for further research to address, including finish quality issues, low carbon material development, and other current limitations and future improvements.

Nevertheless, with the recent technological developments, AC has the potential to transform the construction industry in the North. Similar to other new technologies introduced to well-established markets dominated by conventional technologies, there is always a transition period, and the acceptance and successful transition depends on some impactful factors. Currently, AC is in such a transition period, and a lot more research still needs to be completed. Nonetheless, the AC technology can be a promising solution for the housing crisis in the North.

ACKNOWLEDGEMENTS

This article compiles the findings from two projects on additive construction funded by the National Research Council Canada through the Platform to Decarbonize the Construction Sector at Scale. We extend our deepest gratitude to our colleagues at the National Research Council, Construction Research Centre, especially Yasir Sultan, executive director of the Built Environment Climate Change Initiatives (BECCI); Joon Ha Hwang, Advanced Construction Practices theme lead; and Anca Galasiu, team lead for the Human-Building Interaction Group. Their invaluable support was instrumental in the project's successful completion.

REFERENCES

Agustí-Juan, I., and Habert, G. 2016. An environmental perspective on digital fabrication in architecture and construction. 21st International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA 2016). Melbourne, Australia. http://dx.doi.org/10.52842/conf.caadria.2016.797

———. 2017. Environmental design guidelines for digital fabrication. Journal of Cleaner Production 142:2780–2791. https://doi.org/10.1016/j.jclepro.2016.10.190

BC Housing. 2018. Interim guide to Indigenous housing development and design. http://dx.doi.org/10.52842/conf.caadria.2016.797

Bong, S.H., Nematollahi, B., Nazari, A., Xia, M., and Sanjayan, J. 2019. Method of optimization for ambient temperature cured sustainable geopolymers for 3D printing construction applications. Materials 12(6): 902. https://doi.org/10.3390/ma12060902

Bos, F., Wolfs, R., Ahmed, Z., and Salet, T. 2016. Additive manufacturing of concrete in construction: Potentials and challenges of 3D concrete printing. Virtual and Physical Prototyping 11(3):209–225. https://doi.org/10.1080/17452759.2016.1209867

Bowra, A., and Mashford-Pringle, A. 2021. More than a structure: Exploring the relationship between Indigenous homemaking practices and wholistic wellbeing. Wellbeing, Space and Society, Vol. 2. https://doi.org/10.1016/j.wss.2020.100007

Buchanan, C., and Gardner, L. 2019. Metal 3D printing in construction: A review of methods, research, applications, opportunities and challenges. Engineering Structures 180:332–348. https://doi.org/10.1016/j.engstruct.2018.11.045

Camacho, D.D., Clayton, P., O'Brien, W.J., Seepersad, C., Juenger, M., Ferron, R., and Salamone, S. 2018. Applications of additive manufacturing in the construction industry—A forward-looking review. Automation in Construction 89:110–119. https://doi.org/10.1016/j.autcon.2017.12.031

Camba, J., Contero, M., Johnson, M., and Company, P. 2014. Extended 3D annotations as a new mechanism to explicitly communicate geometric design intent and increase CAD model reusability. Computer-Aided Design 57:61–73. https://doi.org/10.1016/j.cad.2014.07.001

Campbell, T., Williams, C.B., Ivanova, O., and Garrett, B. 2011. Could 3D printing change the world? Technologies, Potential, and Implications of Additive Manufacturing 3.

Coates, K.C.H. 2018. Revolutionary building for the North: 3D printing construction. Ottawa: The Conference Board of Canada.

Demyanov, A., and Popov, I. 2019. Overview of global design experience and a design of a mobil construction 3D printer. Architecture and Engineering 4(4):22–29. https://doi.org/10.23968/2500–0055–2019–4–4–22–29

Dixit, M. 2019a. Life cycle recurrent embodied energy calculation of buildings: A review. Journal of Cleaner Production 209:731–754. https://doi.org/10.1016/j.jclepro.2018.10.230

Dixit, M. 2019b. 3-D Printing in Building Construction: A literature review of opportunities and challenges of reducing life cycle energy and carbon of buildings. IOP Conference Series: Earth and Environmental Science 290: 012012. http://dx.doi.org/10.1088/1755–1315/290/1/012012

Dubois, G., and Gadde, L.-E. 2000. Supply strategy and network effects — Purchasing behaviour in the construction industry. European Journal of Purchasing & Supply Management 6(3):207–215. https://doi.org/10.1016/S0969–7012(00)00016–2

Ellis, L.D., Badel, A.F., Chiang, M.L., Park, R.J., and Chiang, Y.M. 2020. Toward electrochemical synthesis of cement- An electrolyzer-based process for decarbonating $CaCO_3$ while producing useful gas streams. Proceedings of the National Academy of Sciences of the United States of America 117(23):12584–12591. https://doi.org/10.1073/pnas.1821673116

El-Sayegh, S., Romdhane, L., and Manjikian, S. 2020. A critical review of 3D printing in construction: Benefits, challenges, and risks. Archives of Civil and Mechanical Engineering 20: 34. http://dx.doi.org/10.1007/s43452–020–00038-w

Ford, S., and Despeisse, M. 2016. Additive manufacturing and sustainability: An exploratory study of the advantages and challenges. Journal of Cleaner Production 137:1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150

Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C.B., Wang, C.C.L., et al. 2015. The status, challenges, and future of additive manufacturing in engineering. Computer-Aided Design 69:65–89. https://doi.org/10.1016/j.cad.2015.04.001

Garcia de Soto, B., Agustí-Juan, I., Hunhevicz, J., Joss, S., Graser, K., Habert, G., and Adey, B.T. 2018. Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall. Automation in Construction 92:297–311. https://doi.org/10.1016/j.autcon.2018.04.004

Gebler, M. 2014. A global sustainability perspective on 3D printing technologies. Energy Policy 74:158–167. https://doi.org/10.1016/j.enpol.2014.08.033

Ghaffar, S.H., Corker, J., and Fan, M. 2018. Additive manufacturing technology and its implementation in construction as an eco-innovative solution. Automation in Construction 93:1–11. https://doi.org/10.1016/j.autcon.2018.05.005

Hague, R., Campbell, I., and Dickens, P. 2003. Implications on design of rapid manufacturing. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 217(1):25–30. https://doi.org/10.1243/095440603762554587

Han, Y., Yang, Z., Ding, T., Xiao, J. 2021. Environmental and economic assessment on 3D printed buildings with recycled concrete. Journal of Cleaner Production 278:123884.
https://doi.org/10.1016/j.jclepro.2020.123884

Harty, C. 2008. Implementing innovation in construction: Contexts, relative boundedness and actor-network theory. Construction Management and Economics 26(10): 1029 – 1041.
https://doi.org/10.1080/01446190802298413

Hensley, L. 2021. 3D printed houses are here.
https://nationalpost.com/life/homes/3d-printed-houses-are-here

Howe, S.A., Wilcox, B., McQuin, C., and Townsend, J.A. 2013. Faxing structures to the Moon: Freeform Additive Construction System (FACS). In: AIAA SPACE 2013 Conference and Exposition: Los Angeles, California.
https://doi.org/10.2514/6.2013 – 5437

Howe, S.A., Wilcox, B., McQuin, C., Mittman, D., Townsend, J., Polit-Casillas, R., and Litwin, T. 2014. Modular additive construction using native materials. In: Proceedings of the Fourteenth Biennial ASCE Aerospace Division International Conference on Engineering: Reston, Virginia. 301 – 312.
https://spacearchitect.org/pubs/ASCE-2014-Howe.pdf

Kading, B., and Straub, J. 2015. Utilizing in-situ resources and 3D printing structures for a manned Mars mission. Acta Astronautica 107: 317 – 326.
https://doi.org/10.1016/j.actaastro.2014.11.036

Kazemian, A., Yuan, X., Meier, R., and Khoshnevis, B. 2019. Performance based testing of Portland cement concrete for construction-scale 3D printing.
https://doi.org/10.1016/B978-0-12-815481-6.00002-6

Khoshnevis, B. 2004. Automated construction by contour crafting—Related robotics and information technologies. Automation in Construction 13:5 – 19.
https://doi.org/10.1016/j.autcon.2003.08.012

Khoshnevis, B., Thangavelu, M., Yuan, X., and Zhang, J. 2013. Advances in contour crafting technology for extraterrestrial settlement infrastructure buildup. In: AIAA Space 2013 Conference and Exposition, 10 – 12 September. San Diego, California.
https://doi.org/10.2514/6.2013 – 5438

Khoshnevis, B., Yuan, X., Zahiri, B., and Zhang, J. 2016. Construction by contour crafting using sulfur concrete with planetary applications. Rapid Prototyping Journal 22 (5):848 – 856.
http://dx.doi.org/10.1108/RPJ-11 – 2015 – 0165

Kovesi, T., Mallach, G., Schreiber, Y., McKay, M., Lawlor, G., Barrowman, N., Tsampalieros, A, et al. 2022. Housing conditions and respiratory morbidity in Indigenous children in remote communities in northwestern Ontario, Canada. Canadian Medical Association Journal 194(3):E80 – E88.
https://doi.org/10.1503/cmaj.202465

Kreiger, M.A., MacAllister, B.A., Wilhoit, J.M., and Case, M.P. 2015. The current state of 3D printing for use in construction. The Proceedings of the 2015 Conference on Autonomous and Robotic Construction of Infrastructure: Ames, Iowa. Vol. 2 – 3. 149 – 158.

Kreiger, E.L., Kreiger, M.A., and Case, M. 2019. Development of the construction processes for reinforced additively constructed concrete. Additive Manufacturing 28:39 – 49.
https://doi.org/10.1016/j.addma.2019.02.015

Labonnote, N., Ronnquist, A., Manum, B., and Ruther, P. 2016. Additive construction: State-of the-art, challenges and opportunities. Automation in Construction 72:347 – 366.
https://doi.org/10.1016/j.autcon.2016.08.026

Liiv, J., Teppand, T., Rikmann, E., and Tenno, T. 2018. Novel ecosustainable peat and oil shale ash-based 3D-printable composite material. Sustainable Materials and Technologies 17.
htpsi//doi.org/10.1016/j.susmat.2018.e00067

Lim, S., Buswell, R.A., Le, T.T., Austin, S.A., Gibb, A.G.F., and Thorpe, T. 2012. Developments in construction-scale additive manufacturing processes. Automation in Construction 21:262 – 268.
https://doi.org/10.1016/j.autcon.2011.06.010

Ma, G., Sun, J., Wang, L., Aslani, F., and Liu, M. 2018. Electromagnetic and microwave absorbing properties of cementitious composite for 3D printing containing waste copper solids. Cement and Concrete Composites 94:215 – 225.
htpsi//doi.org/10.1016/j.cemconcomp.2018.09.005

Maskuriy, R., Selamat, A., Maresova, P., Krejcar, O., and David, O.O. 2019. Industry 4.0 for the construction industry: Review of management perspective. Economies 7(3): 68.
https://doi.org/10.3390/economies7030068

Mueller, R.P., Howe, S., Kochmann, D., Ali, H., Andersen, C., Burgoyne, H., Chambers, W., et al. 2016. Automated additive construction (AAC) for Earth and space using in-situ resources. Proceedings of 15th Biennial ASCE Conference on Engineering, Science, Construction, and Operations in Challenging Environments.

Native Women's Association of Canada. 2023. Development of a sustainable, affordable, and culturally appropriate housing model—Stage 1.
Development-of-a-Sustainable-Affordable-and-Culturally-Appropriate-Housing-Model.pdf (nwac.ca)

Nematollahi, B., Xia, M., and Sanjayan, J. 2017. Current progress of 3D concrete printing technologies. 34th International Symposium on Automation and Robotics in Construction: 260–267.
https://www.iaarc.org/publications/fulltext/ISARC2017-Paper035.pdf

Nidus3D. 2022. North America's first multi-unit 3D printed homes.
https://nidus3d.com/leamington/

Ocean's North. 2021. Towards a waste-free Arctic.
https://www.oceansnorth.org/wp-content/uploads/2021/03/Towards-a-Waste-Free-Arctic.pdf

Panda, B., Singh, G.B., Unluer, C., and Tan, M.J. 2019. Synthesis and characterization of one- part geopolymers for extrusion-based 3D concrete printing. Journal of Cleaner Production 220:610–619.
https://doi.org/10.1016/j.jclepro.2019.02.185

Penn State. 2024. 3D printing affordable, sustainable and resilient housing in Alaska.
https://www.psu.edu/news/arts-and-architecture/story/3d-printing-affordable-sustainable-and-resilient-housing-alaska/

Perkins, I., and Skitmore, M. 2015. Three-dimensional printing in the construction industry: A review. International Journal of Construction Management 15(1):1–9.
https://doi.org/10.1080/15623599.2015.1012136

Prater, T., Kim, T., Roman, M.C., and Miller, R.P. 2018. NASAÕs centennial challenge for 3D-printed habitat: Phase II outcomes and phase III competition overview. 2018 AIAA Space and Astronautics Forum Exposition: Orlando, Florida.
https://doi.org/10.2514/6.2018–5405

Qaqqaq, M. 2021. "Sick of waiting" A report on Nunavut's housing crisis by Mumilaaq Qaqqaq MP for Nunavut.
https://www.aptnnews.ca/wp-content/uploads/2021/03/Qaqqaq.HousingReport.2021-1.pdf

Rieuf, V., Bouchard, C., Meyrueis, V., and Omhover, J.-F. 2017. Emotional activity in early immersive design: Sketches and moodboards in virtual reality. Design Studies 48:43–75.
https://doi.org/10.1016/j.destud.2016.11.001

Roman, M.C., Eberly, E.A., Mueller, R.P., and Deutsch, S. 2016. NASA centennial challenge: Three dimensional (3D) printed habitat. In: Malla, R.B., Agui, J.H., and van Susante, P.J., eds. Earth and Space 2016: Engineering for extreme environments. Reston, Virginia: American Society of Civil Engineers. 333–342.

Roman, M.C., Kim, T., Prater, T.J., and Muller, R. 2017. NASA centennial challenge: 3D-printed habitat AIAA SPACE and Astronautics Forum and Exposition.
https://doi.org/10.2514/6.2017–5279

Rouhana, C., Aoun, M., Faek, F., and Jazzar, M.E. 2014. The reduction of construction duration by implementing contour crafting (3D Printing). Proceedings of the 22nd Annual Conference of the International Group for Lean Construction: Oslo, Norway.
http://dx.doi.org/10.13140/RG.2.1.1718.4646/1

Sakin, M., and Kiroglu, Y.C. 2017. 3D printing of buildings: Construction of the sustainable houses of the future. Energy Procedia 134:702–711.
https://doi.org/10.1016/j.egypro.2017.09.562

Schuldt, S.J., Jagoda, J.A., Hoisington, A.J., and Delorit, J.D. 2021. A systematic review and analysis of the viability of 3D-printed construction in remote environments. Automation in Construction 125: 103642.
https://doi.org/10.1016/j.autcon.2021.103642

Schutter, G.D., Lesage, K., Mechtcherine, V., Nerella, V.N., Habert, G., and Agusti-Juan, I. 2018. Vision of 3D printing with concrete — Technical, economic and environmental potentials. Cement and Concrete Research 112:25–36.
https://doi.org/10.1016/j.cemconres.2018.06.001

Sheikh, B., and Sharma, P. 2020. Modern and conventional construction methods: A review. International Journal of Research and Analytical Reviews 7:625–629.

Smith, D. 2012. Printed buildings: An international race for the ultimate in automation. Construction Research and Innovation 3(2):26–31.
https://doi.org/10.1080/15623599.2015.1012136

Studios, H. 2018. 3D-printed habitat challenge.
3-D-Printed Habitat Challenge—NASA

Urschel, W. 2017. Urschel wall building machine.
https://youtu.be/QXqwnJTVSsE?si=7sfkEJTTa9se1mgQ

Verhoef, L.A., Budde, B.W., Chockalingam, C., Nodar, B.G., and Wijk, A.J.M. 2018. The effect of additive manufacturing on global energy demand: An assessment using a bottom-up approach. Energy Policy 112:349–360.
`https://doi.org/10.1016/j.enpol.2017.10.034

Wu, P., Wang, J., and Wang, X. 2016. A critical review of the use of 3-D printing in the construction industry. Automation in Construction 68:21–31.
https://doi.org/10.1016/j.autcon.2016.04.005