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TECHNICAL

Advancing Sustainable Housing: The Impact of 3D Printing Technologies

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ABSTRACT

PURPOSE: 3D printing is a new technology that has the potential to transform the building industry, notably in the field of sustainable housing. This study investigates the role of 3D printing in sustainable

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housing by analysing the technology’s current state of art and its implementation in the building sector, resulting in a systematic review.

DESIGN/METHODOLOGY/APPROACH: The study attempts to investigate the different considerations a contractor should take before starting 3D printing. These considerations include technique, material, robotic machinery, structure type, and modelling software.

Initially, a selection procedure consisting of three steps was employed to choose appropriate literature based on predetermined criteria. Next, a bibliometric examination was carried out to recognise the primary developments in safety management aided by automation. Subsequently, there is a discussion about the safety implementations of diverse domains, including construction robotics, virtual reality, building information modelling tools, and artificial intelligence.

FINDINGS: After investigating multiple options for each of the considerations, the paper provides the best choice for each based on intensive research. The Inkjet technique appeared to be the best technique that could be used and modified cementitious powder (CP) will be the optimum material to be used with it. Moreover, the Articulated Robot System was found to be the most advantageous system among other robotic machinery. When compared to high-rise buildings, low-rise structures were proven to be the most suitable type of structure for 3D printing applications. Amongst multiple software, such as AutoCAD and Rhino, Revit was chosen as the most convenient and practical software to be used for 3D printing applications.

ORIGINALITY/VALUE OF PAPER: This paper compared the various options contractors are faced with when adopting 3D printing. Based on an intensive review, a suggestion was made to facilitate the adaptation process for the contractors. One option from each category was chosen, and these options combined could be used by contactors aiming to get into the 3D printing field.

RESEARCH LIMITATIONS: This article acknowledges the emerging field of 3D printing in construction and highlights several limitations. These include the lack of consideration for recent technology advancements, limited availability of data, and the global applicability of the research. Moreover, the paper falls short in providing a comprehensive analysis of the costs of 3D printing technology in the construction industry. Ethical and environmental aspects are not adequately addressed. While the paper suggests specific combinations of methods, supplies, equipment, structures, and software for implementing 3D printing, it is important for businesses to carefully evaluate the suitability of these recommendations to their unique needs and circumstances before integrating the technology into their construction processes.

KEYWORDS: *3D Printing; Sustainable Housing; Sustainable Inkjet; Modified Cementitious Powder; Articulated*

AIM

The goal of this article is to add to the continuing discussion about sustainable housing by investigating how 3D printing can play a role in encouraging more sustainable and affordable housing for communities around the world, resulting in a systematic review. The goal of this systematic review is to extend knowledge, comprehensive study, clarify concepts, or investigate research methodology.

RESEARCH QUESTIONS

- What is the present state of 3D printing technology and how is it being used in the construction industry?

- What are the benefits of 3D printing in green building?
- What are the challenges to the broad use of 3D printing in sustainable housing?
- What are the limitations and drawbacks of 3D printing in the context of sustainable housing?
- What sustainable materials are used in 3D printing to generate more sustainable housing?
- What techniques are used in 3D printing?
- What robotic machinery could be used to build 3D printed houses?
- What type of structure is the most suitable to be 3D printed?
- Which software is the most efficient for 3D printing?

PROBLEM STATEMENT

The construction industry is considered one of the largest and most weathered markets around the world, yielding around US$10 trillion every year in revenue (El-Sayegh *et al.*, 2020). Limited knowledge in the field of automation restricted the introduction of construction 3D printing, which is a result of fear and unknown risks. Investments of the past are catching up with increased landfill accumulation and infrastructure degradation. Nevertheless, with the increase of manufacturing labour productivity arose the decline of construction labour productivity (El-Sayegh *et al.*, 2020). This was due to the low technological applications, linear production, exhaustion of natural resources, and high carbon emissions in the construction industry. There were few initiatives aimed towards sustainable development until the introduction of 3D printing.

LITERATURE REVIEW

Background

3D printing, or additive manufacturing, allows for the automatic fabrication of intricate shapes from a 3D design without need for tooling, dies, or fixtures (Tay *et al.*, 2017). Concrete printing, akin to Contour Crafting (CC), developed by Loughborough University, UK, deposits material layer-by-layer using a large gantry printer (Tay *et al.*, 2017). CC constructs structures using thicker layers without impacting surface quality, with capabilities to embed conduits for electrical, plumbing, and structural reinforcement (Tay *et al.*, 2017). Building Information Modelling (BIM) manages the entire construction process, addressing low productivity and lack of collaboration (Tay *et al.*, 2017). BIM-based 3D printing could bring significant cost and labour savings to the industry, although the integration of BIM and 3D printing still needs more study.

Construction 3D printing often uses cement-based paste with various additives (Lin *et al.*, 2020). Other experiments have used wood-based substances, sustainable bioplastic, and thermoplastic polymers for concrete reinforcement (Besklubova *et al.*, 2021). MX3D, in the Netherlands, created metal structures using a welding compound (Besklubova *et al.*, 2021). The "Antigravity" method allows the production of 3D objects on any surface, independent of slope or smoothness, without additional support (Besklubova *et al.*, 2021). 3D printing uses various materials such as polymers, metals, resins, and ceramics, to create items by layering (Alhumayani *et al.*, 2020). Contrastingly, 3D cob printing constructs buildings from natural materials such as dirt, sand, straw, and water. Cob is applied wet, drying into a solid structure (Alhumayani *et al.*, 2020). 3D cob printing focuses on construction, while 3D printing has a broader range of applications (Alhumayani *et al.*, 2020).

The increasing frequency of natural disasters makes recovery essential (Subramanya and Kermanshachi, 2022). 3D printing can mitigate the environmental impact and logistical issues associated with traditional construction methods (Subramanya and Kermanshachi, 2022). It reduces the carbon emissions from transporting temporary housing to disaster-stricken areas, contributing to sustainability (Weng *et al.*, 2019).

Benefits of 3D printing

3D printing in construction offers sustainability benefits such as waste reduction (Hager *et al.*, 2016). Precise 3D printers produce minimal waste, requiring fewer materials and reducing wood use as less formwork is needed (Xu *et al.*, 2017). Moreover, it enables on-demand production, decreasing surplus materials and damage. 3D printing accelerates construction processes, proving especially useful for disaster relief, providing rapid housing solutions following earthquakes or war (Hager *et al.*, 2016). The consequent material and time savings result in cost-effective construction (Wu *et al.*, 2016).

Adopting 3D printing could also reduce energy use and carbon footprint as fewer steps and materials are needed (Mohammad *et al.*, 2020). Therefore, 3D printing decreases waste, uses energy-efficient techniques, lowers energy use, and promotes sustainable construction (Mohammad *et al.*, 2020) (see Table 1).

Table 1: Limitations of 3D Printing

	Limitation	Description
I	Material	
	Printability	Refers to the ability of the material to be pumped through the nozzle. Dense materials will require force and pressure from machinery to be pumped adequately. Light materials will flow through the nozzle easily, but at the expense of accuracy
	Buildability	Strength of mortar when pumped before setting
II	3D Printer	
	Scalability	Size of project constrained by the chamber volume of 3D printer limiting large scale projects
	Directional Dependency	Direction of printing affecting mortar strength changing the ultimate strength under certain loads
	Geometric Limitation	3D printers lack printing straight-edge corners
III	Design	
	Structural Integrity	High absorption and shrinkage of mortar causes cracks, therefore decreasing structural strength and durability
IV	Construction Management	
	Codes and Regulations	No laws and regulations abiding 3D printing
	Liability issues	No liability assurance in case of machine failure
V	Stakeholders	
	Less Demand for Workers	Automation leads to less demand in construction labour
	New Skillset needed for labour	Higher skillset needed in workers for operation and maintenance of 3D printers

Source: El-Sayegh *et al*., 2020; TWI Ltd, n.d.; Hou *et al*., 2021

METHODOLOGY

This study will utilise a mixed-methods approach, examining prior research to discern the best use of 3D printing for sustainable housing, considering client perspectives. A systematic review, aiming to synthesise and evaluate all relevant data rigorously and methodically, will serve as the primary research strategy (see Figure 1).

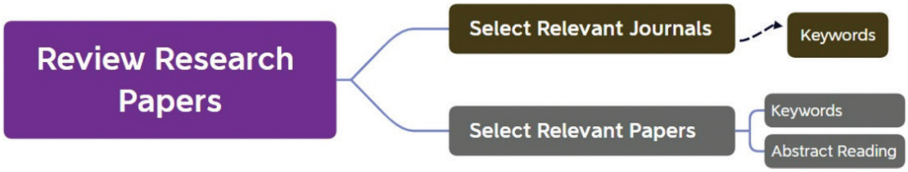

Figure 1: Methodology Map

Source: Constructed by authors

This investigation utilised Scopus, a renowned journal database, to select relevant academic articles. The initial search phrase "3D printing" AND "Construction" AND "Sustainability" was used to focus on the application of 3D printing in sustainable construction. This produced 139 articles; this was reduced to 118 by including only English language articles related to Engineering and Material Science, and published post-2015. A bibliometric analysis was then conducted using VOS viewer on this curated selection.

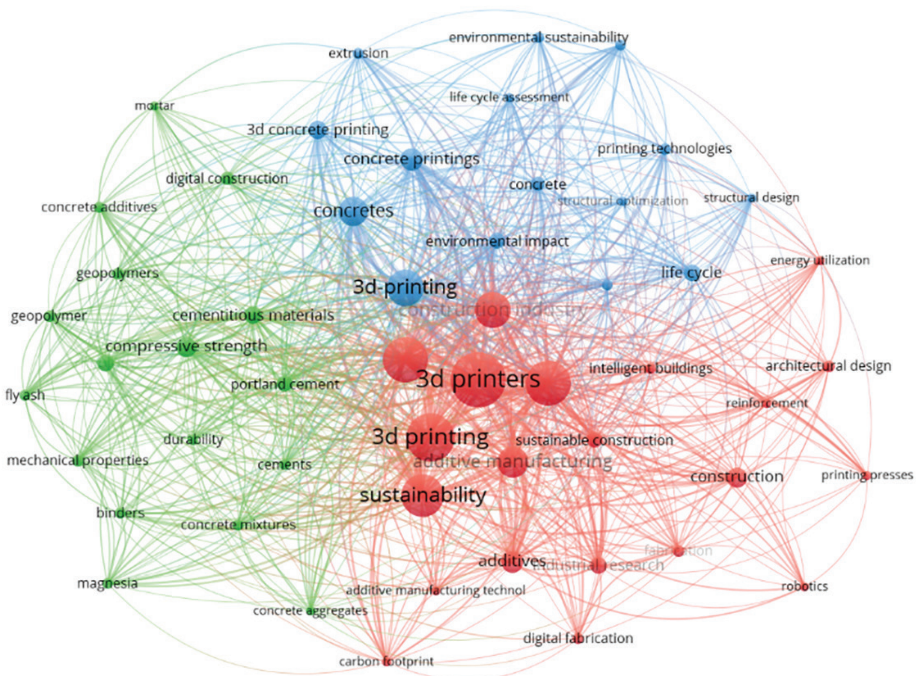

Figure 2: Bibliometric Analysis

Source: Constructed by authors

The results of the bibliometric analysis are depicted in Figure 2. The size of the nodes portrays the occurrences of each keyword, the colour illustrates the different topics, and the links shows the interrelatedness of each keyword within the article pool.

RESULTS AND DISCUSSION

Techniques

3D printing in the construction sector is growing rapidly, with various techniques developed to support this growth. The two primary categories are extrusion-based and powder-based methods (El-Sayegh *et al*., 2020). Contour Crafting (CC) is an extrusion-based technique often employed in 3D printing and was the first to be used for onsite construction (Davtalab *et al*., 2018). CC prints concrete by pumping fluid mortar through a nozzle, with trowels attached to the nozzle tip to smoothen the concrete surface (El-Sayegh *et al*., 2020). CC has advantages such as improved surface quality, faster manufacturing, and compatibility with a wide range of materials (Davtalab *et al*., 2018). However, limitations include its complexity; only vertical extrusions are feasible, the possibility of weaker interfacial areas due to hydrostatic stress, and poor mechanical qualities of the ejected mortar (Ingaglio *et al*., 2019). The inkjet technique is a more recent powder-based method. It distributes a layer of powder or chip form substance over a solid base, followed by a fluid binder to solidify the powder, repeated to create a 3D object (Shakor *et al*., 2019). This technique is more suitable for precast components and requires less human involvement than extrusion-based methods, often leading to a smoother operation and resolution of printing challenges (Shakor *et al*., 2020). Based on the comparison, the inkjet technique seems more advanced than CC for constructing sustainable 3D housing due to its advantages and solutions to the challenges posed by extrusion methods.

Materials

The cement is the most essential component of 3D printing composition, and there are numerous elements or compositions that can be in the cement mixture and different types of cement. In terms of flowability, spreading powder, binding between layers, wettability, porosity, and surface roughness, we will compare commercial powder (ZP151) to modified cementitious powder (CP) for 3DP (Shakor *et al*., 2020). Powders with a high flowability improve the resolution of the printed product, whereas those with a poor flowability reduce it (Shakor *et al*., 2020). There have been no previous comparative investigations on the flowability of cement mortar materials and plaster powder (ZP151) in inkjet 3D printing. The commercial powder (ZP151) from 3DSystems contains a high concentration of gypsum plaster, made of calcium sulphate hemihydrate (Shakor *et al*., 2020). The cementitious (modified) powder (CP) consists of Ordinary Portland Cement (OPC), Calcium Aluminate Cement (CAC), Lithium Carbonate (Li2CO3), and Fine Sand. To speed up the setting period of the cement, lithium carbonate is added as an agent (Shakor *et al*., 2020). The purpose of this is to examine the flowability and resolution of these two powders in inkjet 3D printing. A particle size analyser and a particle size laser distributor were used to accomplish the particle size analysis. Each powder's particle size distribution can affect its flowability, and therefore its appropriateness for inkjet 3D printing. The purpose of this is to investigate the flowability and printing resolution of ZP151 powder and modified cement mortar powder by analysing their particle size distribution (Shakor *et al*., 2020).

The particle size distribution data of five distinct types of powders, represented in terms of D10, D50, and D90 values, were obtained as follows. ZP151, gypsum powder, has a remarkably small particle size distribution, with D10, D50, and D90 values of 1.48µm, 23.07µm, and 70.12µm, respectively. On the other hand, Ordinary Portland Cement has a smaller range with D10, D50 and D90 values of 0.19µm, 8.93µm and 38.46µm, respectively. The particle size of calcium aluminate cement is much higher, with D10, D50, and D90 values of 3.38µm, 79.93µm, and 127.11µm, respectively. Fine sand has the largest particle size of the powders, as predicted, with D10, D50, and D90 values of 83.23µm, 110.51µm, and 147.89µm, respectively. Finally, the particle size distribution of lithium carbonate is relatively small, with D10, D50, and D90 values of 1.63µm, 5.58µm, and 13.56µm, respectively (Shakor *et al*., 2020). These powders' particle size distribution is a key feature that can impact their qualities and behaviour in a variety of applications.

CP has a mixture percentage of 67.8% CAC and 32.2% OPC (Shakor *et al*., 2020). After determining the particle size of each powder, the best blend that is most comparable to the specified commercial powder can be determined heuristically. Furthermore, lithium carbonate accounts for 4.5% of the entire mix (accelerate agent Li2CO3) (Shakor *et al*., 2020). The lithium carbonate contributes to fast setting at a low cost, great early strength, and excellent adhesion and stability. Several of the specimens were made without lithium carbonate and were instead replaced with 5% fine sand (Shakor *et al*., 2020).

Saturation level, volume of binder to volume of powder, and water/cement ration (w/c) were conducted for various samples of ZP151 and CP. The samples obtained four different saturation levels of S100C200, S125C250, S150C300 and S170C350 (S: shell and C: core) (Shakor *et al*., 2020). These results mean that each sample had reached full saturation for the shell and the core, e.g., S100C200 means 100% shell and 200% core. The Vb/Vp for each sample were 0.244, 0.305, 0.366, and 0.415 for S100C200, S125C250, S150C300 and S170C350, respectively. The w/c for ZP151 samples were 0.27, 0.33, 0.40, and 0.46 for S100C200, S125C250, S150C300 and S170C350, respectively, and the w/c for CP samples were 0.31, 0.38, 0.46, and 0.52 for S100C200, S125C250, S150C300 and S170C350, respectively (Shakor *et al*., 2020).

The powder properties of bulk density and surface area for two types of powders, ZP151 and CP, were obtained (Shakor *et al*., 2020). ZP151 had a surface area of 0.999m^2/g and a bulk density of 0.912g/cm^3, and CP had a surface area of 1.021m^2/g and a bulk density of 0.79g/cm^3 (Shakor *et al*., 2020). The surface area for CP is higher than the surface area for ZP151, indicating that CP could possibly have a greater reaction compared to ZP151 (Shakor *et al*., 2020). The higher number of particles on the surface of the powder in CP also suggests that CP is more wettable than ZP151 (Shakor *et al*., 2020). However, the layer thickness on the build chamber has a significant impact on binder penetration and the spreadability of the binder over the packed powder. The bulk density of ZP151 is greater than the bulk density of CP; this means that the porosity of ZP151 is lower than that of CP (Shakor *et al*., 2020). This showed that increasing the bulk density of the powder decreased the porosity of the powder. Overall, this provides important information about the powder properties that can influence the behaviour of the powders during the binder jetting process. These properties need to be carefully considered to ensure successful fabrication of parts with the desired properties. The findings of the experiment showed that 15.83 ± 2.51g of ZP151 where able to move through the openings of the feeding contained in one spreading layer, while the CP had only 12.83 ± 3.12g (Shakor *et al*., 2020).

To conclude, the accuracy of the green part of the specimens was measured in all three axes and found to be very close to the computer aided design (CAD) model. In terms of flowability, spreading powder, binding between layers, wettability, porosity, and surface roughness, the applicability of the inkjet 3DP technology for construction applications utilising modified cementitious powder (CP) was compared to that of commercial powder (ZP151). The findings show that CP is a printable powder, and that the combination of CP with the inkjet 3DP technology is appropriate for building applications (Shakor *et al*., 2020).

3D Printing Robotic Machinery

The two most common and widely prevalent robotic systems used in the 3DP construction industry are the Gantry system and Articulated Robot system (Puzatova *et al*., 2022). The two differ in system reach, mobility, and overall printing accuracy.

The Gantry system operates in the ordinary Cartesian (x,y,z) axes with provision to rotate around the vertical axis allowing the nozzle to move tangentially along the printing direction (El-Sayegh *et al*., 2020; Puzatova *et al*., 2022); this means the printing of straight-edge corners is impossible. When it comes to Gantry systems, first to come to mind is the fact that the system should always be larger than the printed object; this limits the printing of large 3D buildings unless a large enough Gantry system can be provided. Consequently, having a large Gantry system on site poses significant transportation and assembly costs. If applied, Gantry systems do not offer the ability to be moved around in-site to print different buildings unless disassembled and reassembled (Puzatova *et al*., 2022). Therefore, even though Gantry systems offer unlimited printing reach, they lack proper mobility and ease of assembly for efficient printing. The two most common types of Gantry systems are Contour Crafting and Concrete Printing.

The Articulated Robot system, or so-called robotic arm, thrives in greater printing accuracy compared to the Gantry system (Puzatova *et al*., 2022). Nevertheless, due to its limited printing reach, approximately 3m in each direction (El-Sayegh *et al*., 2020), robotic arms are unable to print large 3D buildings. However, robotic arms can be mounted in a roller platform to be moved around the site conveniently to print smaller objects or pre-cast objects offsite and assemble them accordingly (El-Sayegh *et al*., 2020; Puzatova *et al*., 2022). The Articulated Robotic system provides movement around the 3-dimentional axes and rotation around each axis for increased design and printing freedom.

All in all, the Articulated Robotic system provides increased printing accuracy, mobility, and ease of assembly, contributing to increased design freedom and reduced construction costs deeming it the superior choice. The use of each system depends on the size and shape of the building, materials to be used, and site flexibility.

Possible 3D Structures

The advent of 3D printing technology has significantly impacted the construction industry, enabling the creation of structures once deemed unattainable. This technology provides a fast, cost-effective solution to constructing emergency shelters and temporary housing, a vital resource in disaster-stricken areas. It has also proved beneficial in regions experiencing housing shortages, offering an affordable, efficient means of building villas, residential structures, and low-rise buildings such as stores and small offices (Subramanya and Kermanshachi, 2022; Shatornaya *et al*., 2017). Further application of 3D printing technology is found in infrastructure construction, including water treatment facilities, retaining walls, and bridges. This method allows for cost-effective, speedy construction while maintaining precision, enabling the creation of an intricately detailed infrastructure (Budzik *et al*., 2022). High-rise construction has also been revolutionised by 3D printing technology, providing unique architectural aspects and making it possible to build structures with unusual shapes and styles. In addition, it significantly reduces waste production, making it a sustainable option (Hossain *et al*., 2020).

Moreover, 3D printing technology facilitates the creation of sculptures and installations that serve as public art, decorative elements, or even components of building facades. This technology offers virtually unlimited design options, helping designers and artists realise their visions (Liu, 2019). Research indicates that low-rise structures, such as houses, small apartment buildings, villas, and commercial buildings, are the most suited for 3D printing. This technology allows for quick, cost-effective fabrication of building components, which can then be assembled on-site. It also enables the creation of specialised components, such as architectural features and ornamental elements, that would be challenging or expensive to produce using conventional construction techniques. The affordability of 3D printing in the construction industry depends on several factors, including material cost, structure size and complexity, and the availability of skilled personnel (Shatornaya *et al*., 2017).

3D printing technology in construction improves efficiency and safety, especially for low-rise buildings. It offers several benefits over conventional construction techniques, such as reduced material waste, faster construction times, lower transportation costs (Raj *et al*., 2021), and the ability to create precise, customised, uniquely designed high-quality building components. By reducing the need for physically demanding labour, heavy lifting, and exposure to hazardous materials, it significantly lowers the risk of work-related accidents. However, the cost-effectiveness, construction duration, and quality of 3D printed components depend on multiple factors, including the structure, the materials used, the printing method, and the operator's skills (Bazli *et al*., 2023).

Real-world examples support the academic research mentioned above. For instance, Dubai unveiled the world's largest 3D printed two-storey building in 2019, constructed in just two weeks. Similarly, Mighty Buildings in the United States introduced the world's first 3D printed net-zero home in California in 2022, demonstrating the potential and applicability of this technology in constructing low-rise buildings.

Software for 3D Printing

Building design and construction have been completely transformed by the introduction of 3D printing to the sector. By enabling architects and engineers to develop 3D models of buildings and structures that can be produced using different 3D printing technologies, computer-aided design (CAD) software plays a crucial part in this process. The construction sector has access to a wide variety of CAD software, each with specific features and capabilities (see Table 2).

Table 2: Comparison of CAD Software for 3D Printing in the Construction Industry

Software	Cost Comparison	3D Printing Compatibility	BIM Availability	Free Version Availability	Ease of Use
Revit	$$$	Yes	Yes	No	Moderate
AutoCAD	$$	Yes	Limited	No	Moderate
SolidWorks	$$$$	Yes	No	No	Difficult
Rhino	$$	Yes	No	No	Moderate
SketchUp	$	Limited	No	Yes	Easy

Source: Constructed by authors

In conclusion, Revit stands out as a potent BIM tool that is appropriate for managing building projects and compatible with 3D printing technology, despite the fact that there are other CAD software solutions for 3D printing in the construction industry.

CONCLUSIONS (TABLE 3)

Table 3: Summary Table

Considerations	Best Choice	Advantages
Technique	Inkjet	Requires minimum supervision Less material wastage Increased strength and flowability
Material	Modified Cementitious Powder (CP)	Increased flowability and compressive strength Better porosity values Higher spreading Better and increased roughness
Robotic Machinery	Articulated Robot System	Increased printing accuracy and mobility Ease of assembly Increased design freedom Reduced construction cost
Structure Type	Low-rise	Quicker and more cost effective Reduce construction time Increased safety Less transportation time and cost
Software	Revit	Better 3D printing compatibility BIM availability Ease of use

Source: Constructed by authors

LIMITATIONS

Given 3D printing in construction is still emergent, the academic papers used here are fairly recent and may not reflect the most current technology. Therefore, the research and data on 3D printing in construction might be limited and not applicable worldwide. This paper largely focuses on contractors, not decision-making entities such as governments, which could expedite the technology's adoption in construction (Bolotin, 2019).

The paper suggests that businesses keen to employ 3D printing in construction should utilise a specific combination of methods, supplies, equipment, structures, and software. Therefore, before integrating 3D printing into their construction processes, businesses must carefully evaluate the paper's recommendations to see if they suit their unique needs and circumstances (Ariyanto, 2022).

RECOMMENDATIONS AND FUTURE RESEARCH WORK IDEAS

To promote the use of 3D printing in construction, it is vital for governments and businesses to invest in research for developing an effective legal system and building codes. This might involve formulating specific standards, guidelines, and certification programmes for 3D printing experts to ensure its safe and reliable usage (Mayer, n.d.).

Further research should also be focused on 3D printing's potential to support disaster relief efforts. This exploration should extend to other building types, printing methods, and materials, potentially increasing productivity and sustainability. Investigation into other 3D printing systems, such as mobile robotic and gantry-based systems, could offer additional construction possibilities.

New companies aiming to leverage 3D printing in construction should collaborate with specialists and manufacturers to create solutions tailored to their specific needs.

REFERENCES

Alhumayani, H., Gomaa, M., Soebarto, V. and Jabi, W. (2020): Environmental assessment of large-scale 3D printing in construction: A comparative study between COB and concrete. *Journal of Cleaner Production*, Vol. 270, p.122463.

Ariyanto, A. (2022): Construction design for 4.5 bar water tube type boiler using Solidworks 2018 Software. *International Journal Science and Technology*, Vol. 1, No. 3, pp.48-53.

Bazli, M., Ashrafi, H., Rajabipour, A. and Kutay, C. (2023): 3D printing for remote housing: Benefits and challenges. *Automation in Construction*, Vol. 148, p.104772.

Besklubova, S., Skibniewski, M.J. and Zhang, X. (2021): Factors affecting 3D printing technology adaptation in Construction. *Journal of Construction Engineering and Management*, Vol. 147, No. 5, p.04021026.

Bolotin, S.A. (2019): Scheduling of a complex development using Revit and Microsoft Project. In *BIM in Construction & Architecture: proceedings of the 2nd International Scientific Conference* (pp.53-58), St Petersburg.

Budzik, G., Tomaszewski, K. and Soboń, A. (2022): Opportunities for the application of 3D printing in the Critical Infrastructure System. *Energies*, Vol. 15, No. 5, p.656.

Davtalab, O., Kazemian, A. and Khoshnevis, B. (2018): Perspectives on a BIM-integrated software platform for robotic construction through Contour Crafting. *Automation in Construction*, Vol. 89, pp.13-23.

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*, Vol. 20, No. 2, pp.1-25.

Hager, I., Golonka, A. and Putanowicz, R. (2016): 3D printing of buildings and building components as the future of sustainable construction? *Procedia Engineering*, Vol. 151, pp.292-299.

Hossain, M.A., Zhumabekova, A., Paul, S.C. and Kim, J.R. (2020): A review of 3D printing in construction and its impact on the labor market. *Sustainability*, Vol. 12, No. 20, p.8492.

Hou, S., Duan, Z., Xiao, J. and Ye, J. (2021): A review of 3D printed concrete: Performance requirements, testing measurements and mix design. *Construction and Building Materials*, Vol. 273, p.121745.

Ingaglio, J., Fox, J., Naito, C.J. and Bocchini, P. (2019): Material characteristics of binder jet 3D printed hydrated CSA cement with the addition of fine aggregates. *Construction and Building Materials*, Vol. 206, pp.494-503.

Lin, L., Tan, Y.K., Wang, C.H., Kua, H.W. and Taylor, H. (2020): Utilization of waste materials in a novel mortar–polymer laminar composite to be applied in construction 3D-printing. *Composite Structures*, Vol. 253, p.112764.

Liu, J. (2019): The current application situation and development bottlenecks of 3D printing technology in the field of sculpture. In *Proceedings of the 3rd International Conference on Art Studies: Science, Experience, Education (ICASSEE 2019)* (pp.292-294). Atlantis Press.

Mayer, M. (n.d.): Is SketchUp good for 3D printing? *3D Solved*. [Online]. Available at: https://3dsolved.com/is-sketchup-good-for-3d-printing/. Accessed: 2 April 2023.

Mohammad, M., Masad, E. and Al-Ghamdi, S.G. (2020): 3D concrete printing sustainability: A comparative life cycle assessment of four construction method scenarios. *Buildings*, Vol. 10, No. 12, p.245.

Puzatova, A., Shakor, P., Laghi, V. and Dmitrieva, M. (2022): Large-scale 3D printing for construction application by means of robotic arm and Gantry 3D Printer: A Review. *Buildings*, Vol. 12, No. 11, p.2023.

Raj, P.V., Teja, P.S., Siddhartha, K.S. and Rama, J.K. (2021): Housing with low-cost materials and techniques for a sustainable construction in India-A Review. *Materials Today: Proceedings*, Vol. 43, pp.1850-1855.

Shakor, P., Nejadi, S., Paul, G. and Malek, S. (2019): Review of emerging additive manufacturing technologies in 3D printing of cementitious materials in the construction industry. *Frontiers in Built Environment*, Vol. 4, p.85.

Shakor, P., Nejadi, S., Paul, G. and Sanjayan, J. (2020): Dimensional accuracy, flowability, wettability, and porosity in inkjet 3DP for gypsum and Cement Mortar Materials. *Automation in Construction*, Vol. 110, p.102964.

Shatornaya, A.M., Chislova, M.M., Drozdetskaya, M.A. and Ptuhina, I.S. (2017): Efficiency of 3D printers in Civil Engineering. *Construction of Unique Buildings and Structures*, Vol. 9, No. 60, pp.22-30.

Subramanya, K. and Kermanshachi, S. (2022): Exploring utilization of the 3D printed housing as post-disaster temporary shelter for displaced people. *Construction Research Congress 2022* (pp.594-605). 9-12 March 2022, Arlington, Virginia.

Tay, Y.W.D., Panda, B., Paul, S.C., Noor Mohamed, N.A., Tan, M.J. and Leong, K.F. (2017): 3D printing trends in building and Construction Industry: A Review. *Virtual and Physical Prototyping*, Vol. 12, No. 3, pp.261-276.

TWI Ltd (n.d.): What are the advantages and disadvantages of 3D printing? *TWI*. [Online]. Available at: https://www.twi-global.com/technical-knowledge/faqs/what-is-3d-printing/pros-and-cons. Accessed: 20 February 2023.

Weng, Y., Ruan, S., Li, M., Mo, L., Unluer, C., Tan, M.J. and Qian, S. (2019): Feasibility study on sustainable magnesium potassium phosphate cement paste for 3D printing. *Construction and Building Materials*, Vol. 221, pp.595-603.

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*, Vol. 68, pp.21-31.

Xu, J., Ding, L. and Love, P.E. (2017): Digital reproduction of historical building ornamental components: From 3D scanning to 3D printing. *Automation in Construction*, Vol. 76, pp.85-96.

BIOGRAPHY

Yara Abu Jbarah, a civil engineer, possesses an academic foundation in civil engineering and is presently working as a graduate teaching assistant while pursuing a master's degree in construction management. Yara demonstrates a diverse set of skills, specifically in areas such as construction management, scheduling, project management, and sustainable construction. Her committed dedication to sustainable and inventive solutions showcases her profound enthusiasm for making a notable difference within the industry of civil engineering.

Mohamed Shalabi is a passionate civil engineer with a strong focus on creating efficient and sustainable infrastructure. With five years of industry experience, he actively integrates renewable energy, green building techniques, and resource efficiency into construction projects. His attention to detail and collaborative mindset delivers high-quality results while meeting client requirements and industry standards. Committed to continuous professional growth, Mohammed stays updated with the latest sustainable design and construction methods. By combining his civil engineering expertise with a deep passion for sustainability, he strives to make a positive impact and create a greener future.

Ziad Ahmed is a highly motivated civil engineer based in Dubai, UAE. With a strong academic background in civil engineering and a current pursuit of a master's degree in construction management, Ziad is equipped with a comprehensive skillset in structural design, project management, and construction practices. Ziad's focus on sustainable and innovative solutions demonstrates his commitment to creating a positive impact in the field of civil engineering.

Abdulaziz Salah Alshaikh is a graduate teaching assistant pursuing his MSc in Construction Management following his degree in Civil Engineering at the American University of Sharjah. Knowledge in the field of Civil Engineering widened his horizons to the current advancements paving through the construction market. The present tools, processes, and materials are only some of the concepts in question. Abdulaziz is keen to prosper in the current construction market through his prevalent leadership skills, authenticity, faith, and determination. He believes that he could be one of the leading figures of tomorrow.

Prof. Salwa Mamoun Beheiry is a Professor of Civil Engineering at the American University of Sharjah. Her research interests revolve around sustainable infrastructure and capital project performance. She is also a recipient of various prestigious honours and awards throughout her academic and industrial career. Before starting her doctoral program at UT Austin, she worked with Independent Project Analysis Inc. in Ashburn, Virginia, as analyst/consultant. She obtained her PhD in Civil Engineering from the University of Texas at Austin, a Master of Science from the George Washington University and a First-Class Honours Bachelor of Science from Reading University (UK).

