Construction Robotics
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A guided approach for utilizing concrete robotic 3D printing for the architecture, engineering, and construction industry

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Abstract
The emerging field of robotic 3D printing offers practical alternatives to conventional building methods that are currently used in the Architecture, Engineering, and Construction (AEC) industry. Robotic 3D printing has many advantages over the conventional construction as it reduces human error, is relatively inexpensive, and opens the door to the creative complex designs while reducing the amount of expertise required to complete the construction process. At present, there is a shortage of resources offering guidance on how to utilize the available technology. Thus, it is often difficult for researchers and practitioners alike to find the right information and make informed decisions relative to their specific applications. In this paper, we provide such a resource by gathering data from previously constructed projects in the form of a categorical study, which paves the way for accessing the most recent information regarding the robotic 3D printing technology of interest. We illustrate the latest methods and techniques used in the field and describe the hardware used. We also use the resulting classification methods to present a decision-making workflow to streamline the process of selecting the most appropriate approach. We also examined and performed a detailed analysis on three case studies of prominent buildings that have been constructed using 3D printing technology. The categorical parameters were selected carefully to form a clear, informative distinction between the buildings. Printing method and motion type were the most important parameters when it comes to robotic 3D printing. A new database was created and demonstrated to elucidate the types of the additive manufacturing that can be used. By analyzing the data, we hope to facilitate the development of new structures as they relate to 3D printing in the AEC industry.

Keywords Robotic 3D Printing · Concrete · Construction · Taxonomy · Decision

1 Introduction

As we head towards an era of rapid digital development, industries are racing to catch up to the demands of a new world that calls for changes to the conventional standards of production (Mathur 2016). The shift towards improved efficiency calls not only for an increase in manufacturing speed, but also for an increase in production complexity as trends continue to shift towards automation and customizability (Linner and Bock 2013). For a long time, the Archi- tecture, Engineering, and Construction (AEC) sector has relied heavily on traditional methods of manufacturing (Achillas et al. 2017), which are limited in several ways. For one, commonly used building procedures, such as injection molding, heavily rely on manual labor, waste large amounts of material, and require a lot of time and expertise. Furthermore, current construction methods carry a significant

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environmental footprint. Research has shown that the building construction process con- sumes a calculated 5.67% of energy globally and is responsible for 6.80% of greenhouse emissions worldwide. These numbers can go up to 39.12% and 68.78% when performing the calculations on an urban scale (Li et al. 2019). A solution is needed to fix this issue. On a global scale, ensuring that the methods of production are environmentally friendly is the only way to reach sustainable development, without resulting in large-scale long-term damage.

Modern methods of construction seek to solve this problem by placing sustainability at the forefront. Recent innovations in building technology have attempted to move work offsite and into the factory to improve efficiency and reduce energy consumption. Processes have begun heading towards methods such as preassembly, prefabrication, modular buildings, and offsite production and manufacturing to manage common problems (Rahman 2014). One study found that relying on prefabrication, a construction procedure that involves breaking down buildings into smaller modular units that are manufactured offsite and assembled at the building location, reduces construction waste by up to 52% (Jaillon et al. 2009). While prefabrication still relies largely on traditional technologies, there is potential for future application, especially when combined with additional novel technologies such as Computer Numerical Controlled (CNC) subtractive production of prefabricated components. Such integration allow for a full customization of steel and wood components as opposed to the traditional mass production of elements.

Similarly, additive manufacturing has garnered a lot of attention in recent years for having the potential to significantly support modern manufacturing methods, enable entirely new development techniques, and expand current construction capabilities (Pereira et al. 2019). 3D printing technology has developed to include concrete printing using robotic arms and gantry systems. For the construction of buildings, this process involves the continuous extrusion of layers of concrete material to manufacture a desired structural design using certain automated mechanisms. These methods have facilitated the automation of building and construction procedures in a way that eliminates human involvement in potentially dangerous tasks while increasing building efficiency (Tay et al. 2017). The environmental impact is significant when utilizing additive manufacturing over traditional manufacturing methods. This is because additive manufacturing can significantly reduce material wastage and result in increased resource efficiency.

Extensive research on the topic has shown that additive manufacturing offers a flexibility that is not present in traditional construction methods. Generally, additive manufacturing has been found to be a more appropriate method of construction for production procedures involving higher level of complexity (Pereira et al. 2019). Due to its increased level of accuracy and high production speed, 3D printing provides an appropriate solution for buildings involving a high degree of customization features.

The real potential of additive manufacturing in construction comes from the real applications of 3D printed buildings that have recently been built around the world (Sakin and Kiroglu 2017). A deeper look at these case studies shows that some instances utilized 3D printing to entirely develop the buildings' indoor and outdoor components with minimal human interference. Furthermore, these instances merged the building's insulation with the natural ventilation during the construction process to ensure that the final structure had sustainable low-energy operation on the long term. In addition, the use of local materials and the re-use of discarded materials added to the projects' reliability and their value to the environment since it resulted in minimal material wastage. Projects that utilize alternative printing methods, such as the 3D printing of metal or polymer an additional significant impact on the future of the 3D printing of buildings. Concrete remains to be the most widely used element in the building process. It is also the most impactful from a sustainability perspective. It could be less probable given the current technology and established processes, that the construction industry will entirely shift to using alternative elements in buildings in the near future. It is more likely, however, that new technology can enable those processes to become less wasteful and more sustainable over time. It is for this reason that we focused almost entirely on the use of concrete as the main 3D printing element in architecture, engineering, and construction procedures in this paper.

However, for all the benefits offered by 3D printing to the AEC sector, it is not without its limitations. Firstly, additive manufacturing is reliant on technologies that may not be readily accessible in all locations (Sakin and Kiroglu 2017). Additionally, established cost models and industrial development procedures are more applicable to traditional construction methods. As a result, developments in construction methods must continuously prove reliable in terms of a cost structure to be more widely used in the future. Finally, additive manufacturing is not a "one-size-fits-all" process. From an outsider's perspective, this may seem overwhelming and complex.

While experience with the technology is beneficial to utilizing it to its full advantage, the heavily automated 3D printing features makes the technology very accessible. Bridging this knowledge gap requires the existence of necessary resources that are readily available and able to provide clear references to existing use cases of the technology, as well as offer guidelines and offer direction for future projects. While research continues to advance in this field (Sati et al. 2021) there is a lack of published articles that provide such a reference. Furthermore, there is a need for studies that categorize

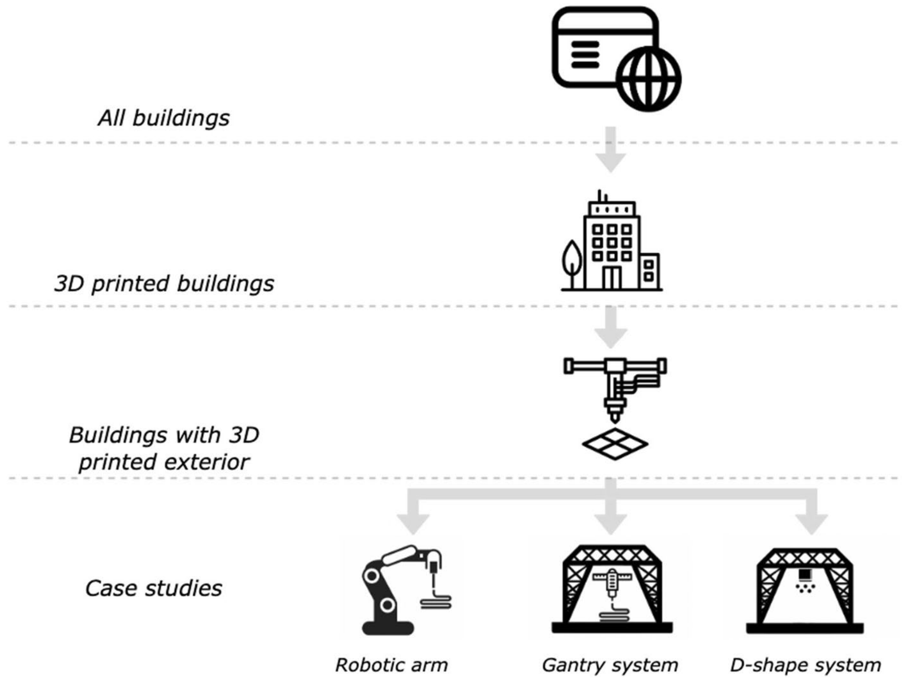

Fig. 1 Flowchart of the data extraction process used to narrow down the buildings analyzed in this paper

existing research in a way that enables future users to make the most out of the available knowledge. This paper aims to fill this gap by presenting a taxonomy of 3D printed buildings around the world. We then use this knowledge to form a decision-making flowchart that enables users to determine the best 3D printing method based on their structural constraints and considerations. By doing so, we aim to provide a clear resource and guideline for individuals looking for novel methods of production that are more sustainable and efficient.

2 Analysis methods

Before we can formulate an analysis, we must define the data that will be considered for classification during the study. This data will form the basis of the taxonomy that we will then develop in this paper. The constraints we placed on the data search for this paper were as follows (Fig. 1). In the initial search, we gathered data on buildings that were fully or partially constructed using 3D printing technology. We then narrowed down the search to only include structures that were only built within the past 50 years. From those, we considered structures that utilized 3D printing technology to construct substantial parts of the exterior of the building. At this point, it is important that the process is formulated in such a way that it can establish a justifiable process to allow researchers to reasonably extract information regarding the viability of 3D printing technologies for their AEC applications. To ensure that the data gathered is relevant and up to date, the buildings will be moderately evaluated based on their ability to answer three questions that related to 3D printing and AEC.

1. Does this building utilize methods that are relevant and are relatively recent with robotic 3D printing technology at the time of writing this paper?
2. Is the building process consistent with robotic 3D printing methods being used in the archi- tecture, engineering, and construction (AEC) field?
3. Are the techniques that were used widely adaptable and relevant to the future of 3D printing in the AEC field?

If the answer to all three criteria is yes, we concluded that the data from this building can be used to formulate the parameters needed to complete a taxonomy database that can become a new addition to a resource material for those wanting to enter the field and eventually, accelerate the implementation of robotic 3D printing in AEC.

Once the relevant buildings have been narrowed down based on the criteria, three of the buildings will be analyzed in depth as cases studies. During the analysis, we will consider five main factors that demonstrate the readiness of those buildings for present and future applications. The restructured taxonomy of the existing materials will be presented in the form of categories that correspond to different combinations of construction systems, printing method, motion type, building technique, and structure size. We do this to inclusively demonstrate examples for a variety of potential applications for 3D printing in construction. For each case study, we will take into consideration five main factors that impact its efficiency and applicability to real world solution on a large scale. The five factors are:

- Energy consumption
  Consumption of energy is a particularly important factor when considering the sustainability and future applicability of a building. While evaluating the energy efficiency of the structures under consideration, we will consider both the active and passive methods that have been accounted for within the building, including heating, ventilation, and air conditioning systems (Pérez-Lombard et al. 2008). This in addition to the relevance of the printing materials used and their ability to contribute to a reduced energy consumption standard.
- Cost–benefit analysis
  The construction process is often rife with deadlines and financial constraints. Ultimately, a construction project is an investment that relies on the completion of certain milestones within specified timeframes and budgets due to the financial cost of delays. It is therefore a significant benefit if a new technology can provide the added value of reduced construction times, especially if this can be accomplished with reduced manpower. In this paper, we examine the time cost and financial costs required to build a structure using 3D printing as compared to traditional methods.
- Expertise involved
  The financial cost increases as more experts are required to develop or maintain a procedure. If a new technology can only be managed with the presence of highly skilled individuals when compared to traditional methods, this acts as a major adoption criteria for this technology. This also greatly impacts the scalability of the procedure as an increase in automation can result in a larger number of buildings being developed in a shorter amount of time. We will analyze the methods used in 3D printed structures and compare how much of the procedures can be automated when compared to traditional methods. We also analyze the cost of automation between the two methods to determine the applicability of each process.
- Structural stability
  The most important element of a building is whether it is structurally sound. Traditional AEC methods rely on several tried and tested steps that ensure that the building can resist environmental factors and can withstand the test of time. To compare the ability of 3D printing technology to compete in this area, we studied the foundational and structural stability of the buildings being analyzed when compared to similar structures that have been built using traditional methods.
- Sustainability
  As we progress towards a more environmentally-friendly approach, it becomes important to find materials and building processes that are both biodegradable and durable at the same time (Han et al. 2021). The balance can sometimes be difficult to obtain but can be offset if the material is accompanied by AEC processes that reduce the overall carbon footprint. As a result, we studied the materials and process used to evaluate if 3D printing technology can provide a pathway to achieving this balance when compared to traditional methods.

Once the data from the case study evaluations as well as the general evaluations of the remaining buildings have been obtained, these will be used to develop a taxonomy of 3D printed buildings. Their role in future construction development based on their novelty and projected contribution with regard to the five factors mentioned above will also be discussed.

3 Results

The taxonomical categorization is dependent on several parameters that particularly distinguish categories of 3D printed buildings based on the potential impact that they may have on the AEC industry. It is important to note that in line with the inclusion criteria that requires the building process be consistent with robotic 3D printing methods being used in the AEC industry, the taxonomy considered only buildings that utilized materials that can withstand high stresses. Therefore, buildings that used polymers were excluded from the categorization. In addition, four parameters were selected to achieve a clear classification for the 3D printed construction (Fig. 2). The criteria for selecting each parameter to classify the constructions that used the 3D printing technology were determined to demonstrate the methodology of each structure. Each of the four taxonomy parameters is explained in detail below.

3.1 Printing method

The method of printing describes the general process used to construct the building being observed. We categorized each building into one of three categories based on whether it utilized Contour Crafting, Concrete Printing, or D-Shape printing as its main printing method. Contour Crafting is an additive construc- tion method that uses computer-controlled movement system with a nozzle attached to deposit material. A trowel is attached to the nozzle head to create the smooth surface finish after the material get deposited (Khoshnevis 2004; Buswell et al. 2020). Contour crafting is a modern layered fabrication technology which has a promising future in automated

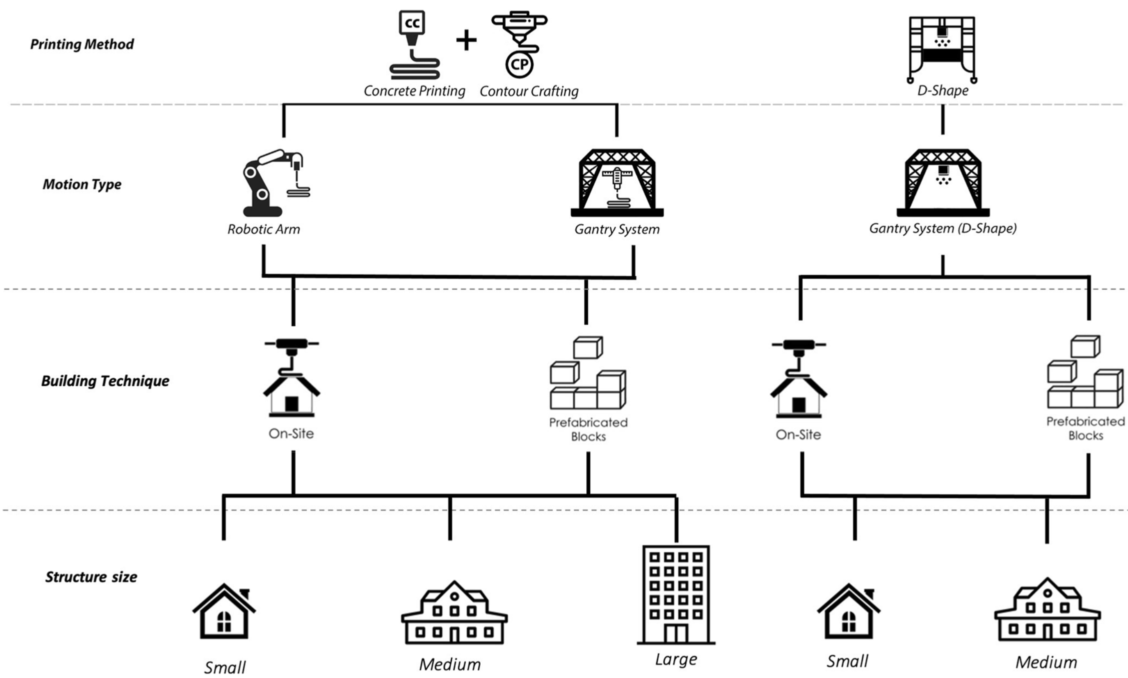

Fig. 2 Robotic 3D printing flowchart demonstrating the taxonomy parameters used in the categorization procedure

construction of both full structures and sub-components (Khoshnevis 2004). Using this process, a single house, or a colony of houses, each with possibly a different design, may be automatically constructed in a single run. Contour Crafting has been cited as one of the very few feasible approaches for building structures on other planets.

Concrete printing on the other hand is a construction process for fabricating innovative complex geometrical concrete designs using layer- based additive manufacturing methods. This method is also known as "free-form construction". This process can be performed in different ways using different systems, but overall follows the same basic principles as the typical desktop 3D printing procedures. A 3D model is designed using any CAD software before being converted into G- code and sent to a 3D printer (Lim et al. 2012). This procedure requires the presence of controllers to synchronize the devices and software (Buswell et al. 2020; Le et al. 2012; Lim et al. 2011).

The third printing method is D-Shape printing. This is a digital construction method that is mainly used by architects to create exotic parametric designs for aesthetic purposes (Lim et al. 2011). This method relies on layer-based construction, and mainly utilizes sand as a construction material. The printing system drops an "ink binder" that solidifies each layer until the full shape is constructed (Buswell et al. 2020; Craveiro et al. 2019). The D-shape Method is also producing whole buildings or building blocks. This method allows to produce the structures off-site (Cesaretti et al. 2014).

3.2 Motion type

It is important to consider the motion type of the 3D printer in the selection pro- cess as this factor can impose restrictions on the build volume. Additionally, some motion types are considered simpler to manage and control as compared to the other types. The motion type needs careful consideration due to a structure's size and shape (Malaeb et al. 2019). Throughout this section, a robot is defined as an automatically controlled, reprogrammable, multi-purpose, manipulative machine with several degrees of freedom, which may be either fixed in place or mobile for use in industrial automation applications as established in previous literary works (Wallén 2008).

The movement control software depends on the type of motion of the system (Al Jassmi et al. 2018). For pump control and extrusion rate parameters, these are based on actual testing and can only be improved by doing iterations and optimization between each run. Internal communication is required between all the software (Lim et al. 2016) and the use of multiple software and rigorous feedback loops are required to achieve the final result. While some approaches have attempted to develop verification systems to ensure deposition accuracy, errors can still occur due to robot dynamics, material self-deflection, material coiling, or timing shifts, particularly in the case of multi-material prints (Sutjipto et al. 2019).

The gantry system is a common 3D printing motion type that consists of a gantry straddling the printing head and nozzle system. The gantry supports the printer head and positions it according to X, Y, and Z coordinates (Malaeb et al. 2019; Hussein 2021). A gantry system will have a dimensional limitation because of its dependence on the size of the gantry, which also limits the axes of printing and presents an obstacle when considering implementation in AEC-related applications (Zhang et al. 2018). On the other hand, the arm-based system overcame the complications related to the scalability and limitations in the movement envelope. The system has the capability of printing in 6 axes, which makes it possible to be implemented in construction sites. The robotic arm poses fewer dimensional limitations and is accompanied by automation software that simplifies the controls (Wu et al. 2018). One major concern with using a robotic arm is the lack of mobility after finishing one structure around the radius of the arm (Malaeb et al. 2019; Zhang et al. 2018; Wu et al. 2018). Robotic arms come in different working envelopes to accommodate large-scale structures. Furthermore, smaller collaborative robots can be used instead of one large robotic arm. This provides the advantage of building in smaller spaces that might be challenging for other systems. All systems still require the presence of a mixer and a pump at a nearby location. The main disadvantage of the robotic arm system is the vertical reach limitation (Wu et al. 2018).

3.3 Building technique

The 1990s saw an increase in the developments in direct manufacturing techniques (Gardiner, 2009). The most notable technique consisted of an additive manufacturing process that produced three dimensional structures using either automated curing or deposition of layers of a certain material (Cesaretti et al. 2014). While creating the tax- onomy presented in this paper, we considered whether the structure was built onsite, or whether it was prefabricated somewhere else and assembled onsite. Prefabricated structures can be very large without requiring a larger 3D printer since the structure is segmented into smaller parts that are printed separately and later assembled at the building location. On the other hand, structures that are printed entirely onsite require less human interference and are usually completed faster. The material properties and parameters need to be considered for the materials to be used in large-scale 3D printing in construction (Panda et al. 2019a). The balance of flowability and buildability is crucial for the success of the printing process (Cho et al. 2020; Chaves Figueiredo et al. 2019). Consistency in flowability is important for any type of 3D printer (Malaeb et al. 2019). In addition, extrudability has an impact on the transportation and the pumping of the fresh concrete to the nozzle so that the extrusion has a continuous flow (Le et al. 2012; Soltan and Li 2018). As a result, the material used has a significant impact on whether a structure can be prefabricated or whether it must be built on-site.

A standard concrete mix consists of water, aggregate, and cement. The difference between different mixes and their properties is due to the varying ratios of the three base components (Panda et al. 2019b; Marchment et al. 2019). Achieving the best mix for 3D printing is an iterative process that attempts to achieve certain rheological requirements prior to construction. The standard criteria present a balance between compressive strength and workability. The material flowability also needs to be considered while maintaining buildability (Malaeb et al. 2019; Wu et al. 2018). Standard or traditional concrete mixes might not be able to achieve the rheological requirements. Therefore, new materials have recently been introduced to meet these needs for 3D printing applications. For example, fiber reinforced concrete was tested and used for the 3D printing of small structures (Zhang et al. 2018). Other projects introduced a geopolymer concrete as a more balanced material for 3D printing (Xia and Sanjayan 2016). Controlling material properties, however, places limitations on component design, as geometrical conformity leads to constraints on how sophisticated the process can be (Buswell et al. 2018). The properties to consider include: workability of the mix, material deformation, hardened properties, geometric conformity, and design freedom. Reinforced concrete is often used in the building process and requires additional considerations during 3D printing. Moving forward, computational methods are needed to analyze and optimize structural capacity within the constraints of 3D printing methods to overcome these issues.

3.4 Structure size

Structure size is important due to its relevance to many of the parameters mentioned above. As such, we included a sizing categorization within the taxonomy to demonstrate the limitations of each parameter. The sizing categories were identified based on the average dimensions of the projects that were gathered and analyzed within this study. We categorized each structure into small, medium, or large structures based on the following. A small-scale building is any building structure that has a floor area of up to 20 m^2. The medium scale consists of buildings with a floor area greater than 21 m^2 but less than 100 m^2 while anything larger than 100 m^2 was considered a large-scale structure.

4 Taxonomy

4.1 Building Categorization

Figure 3 was divided into three columns. The first section lists the buildings that fall under the contour crafting

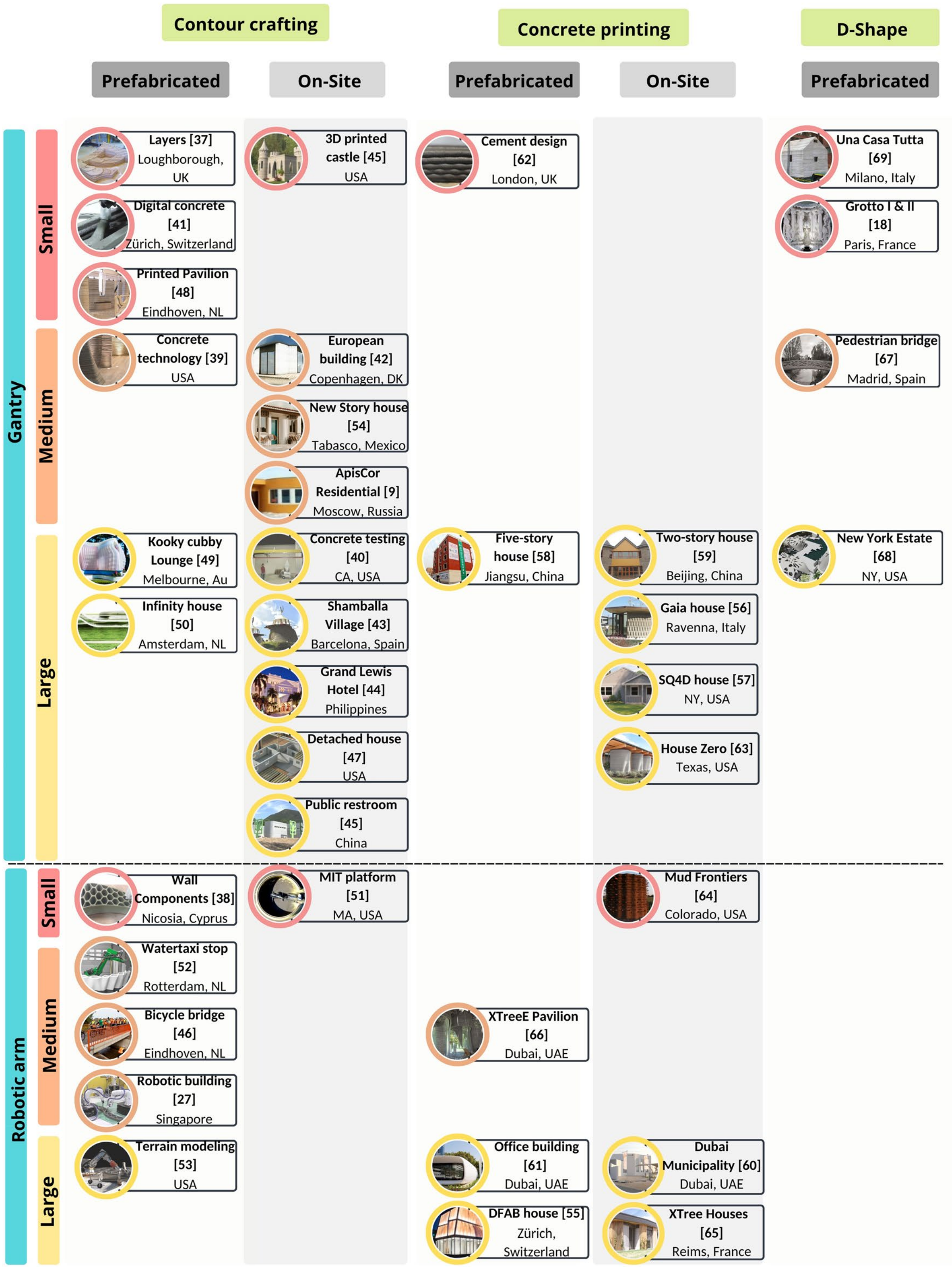

Fig. 3 A taxonomy of recent works involving 3D printing for AEC applications categorized by three printing methods: contour crafting, concrete printing, and D-Shape printing

category, while the second column lists those that used the concrete printing method. Lastly, the third column lists are those that were completed using the D-Shape method.

Contour crafting is the most used method for robotic 3D printing in construction [e.g. (Sakin and Kiroglu 2017; Le et al. 2012; Zhang et al. 2018; Holt et al. 2019; Hossain et al. 2020; Salet et al. 2018; Khorramshahi and Mokhtari

2017; Ahmed et al. 2016; Projects 2022; Nadarajah 2018; Keating et al. 2014, 3DCP Watertaxi Stop 2022; Lim et al. 2009; Kontovourkis and Tryfonos 2020; Kamran and Hussein 2020; Kazemian et al. 2019; Wangler et al. 2016; Pessoa et al. 2021; Cruz et al. 2019; Horowitz and Schultz 2014; ICON 2022)]. Many projects that used the concrete printing method were done on-site, or using prefabricated blocks that were later exported to other locations to be built [e.g. (DFAB HOUSE 2022; Dancel and Dancel 2023; Printed House 2022; Yossef and Chen 2015; Sanjayan and Nematollahi 2019; Alhumayani et al. 2020; Zhang et al. 2019; Albar et al. 2020; ICON: House Zero 2022; San Fratello and Rael 2020; Westerlind and Hernandez 2020; XTreeE: Pavillon in Dubai (project) 2020; Meibodi and Taisne 2017; Tampi 2015; ScholarWorks et al. 2023; Wawrek 2019)]. The D-Shape method is a unique and a relatively new method of robotic 3D printing. Applications of this method generally involve the development of structures that emphasized on the aesthetic characteristics but have most recently been used to build large-scale construction projects as well [e.g. (Craveiro et al. 2019; Meibodi and Taisne 2017; Tampi 2015; ScholarWorks et al. 2023)].

4.2 Case studies

For each printing method, we will consider a case study that represents the most prominent features involved in the construction process. Each of the three case studies was selected to represent a different use-case 3D printing technology in construction. The first case study considered a five-storey residential building in China using the Contour Printing method. The second case study examined the use of 3D printing to develop a standalone residential house using the contour crafting method. The third case study explored the use of 3D printed buildings in disaster affected areas. To reduce comparison bias, all three case studies were printed using the gantry system. We will consider the five factors of energy consumption, cost–benefit, expertise required, structural stability, and sustainability of materials. to determine the likelihood of success. Furthermore, we compared these features with similar structures that were built using traditional construction methods to determine the viability of using additive manufacturing to successfully propel the construction industry forward.

4.2.1 3D Printed house with contour crafting

A company named Apis Cor, developed the 3D printing technology to demonstrate the possibility of utilizing contour crafting to construct homes in short periods of time at a reduced cost (Fig. 4). The entire house included a living room, a bathroom, a kitchen, and a hallway. The house was built using the contour crafting method and currently stands in a town close to Moscow, Russia.

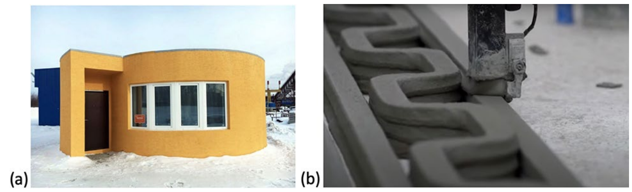

Fig. 4 A sample of a contour crafted structure. **a** A 37 m^2 3D printed residential home by Apis Cor. **b** Image showing the construction of the building using contour crafting. It was printed using a gantry system that printed the structure directly on-site in Moscow, Russia (Sakin and Kiroglu 2017)

- Energy consumption
  A research study performed by the Technical University of Kosice in Slovakia examined a number of 3D printed buildings, including the Apis Cor building to determine the energy saving capa- bilities of deploying 3D printing in construction (Wawrek 2019). The study found the materials used and the shorter building times resulted in the production of minimal construction waste compared to using traditional methods. A significant reduction in carbon dioxide emissions was noted and less energy was consumed overall. Furthermore, the study examined minor structural changes that can be made to the house in future buildings that would allow it to save more energy and become a zero net energy building. This means that the net energy balance of this building could be equal or near to zero, even when using concrete.
- Cost–benefit analysis
  The 3D printing method that was used to construct this home was able to significantly reduce construction times and costs. The home was built entirely on-site in 24 h. Furthermore, this was found to save up to 70% of construction costs. The cost of the building procedure was $10,134. This amount is equivalent to $275 for every square meter and accounts for every aspect of the interior and the exterior including the foundation, the roof, the insulation, and the finishes. For reference, the doors and the windows were the most expensive elements of the house.
- Expertise involved
  To construct the house, the company developed a specialized automatic unit of mixture and supply as well as a mobile 3D printer. The shape of the building was designed by specialists to highlight the capabilities of 3D printing for constructing any desired building shape. The whole building was printed as a single unit including the walls and partitions in one day which led to a significant reduction in the labor required. Furthermore, the building

was printed directly on-site and required no assembly or transport from off-site facilities.

- Structural Soundness

  The house was built in a location that can be characterized as having a harsh winter climate. Although the roof is flat, it is capable of enduring snow load specifications for buildings in that area. This was achieved by incorporating patches of polymer membrane that were linked together using hot air. The house was deemed habitable and was in line with the structural guidelines established for houses of similar sizes. The flexibility and adaptability of the 3D printing process allows for different kinds of installations, integrations, and fittings to be included throughout the building process.
- Sustainability

  All the foundations and walls of this building were printed using a concrete mixture. Additional elements, such as windows, fixtures, doors, and furniture, were added after the construction was completed. At the end of the building process, a fresh coat of paint was applied to the exterior of the building. Overall, the materials used for this building were similar to those used for in the construction of a similarly sized building using traditional construction methods. However, the construction waste was significantly lowered as a result of using 3D printing.

4.2.2 Concrete printing a five-storey building

In this case study (Fig. 5), we considered a 3D printed building in Suzhou, China that was built using concrete printing and a gantry system (Yossef and Chen 2015). The floor area of the building was 1100 m^2 which is too large for a gantry system to be able to directly print. As such, the building's construction blocks were prefabricated offsite before being transported to the construction location for assembly (Prasittisopin et al. 2018). The printer used to build the

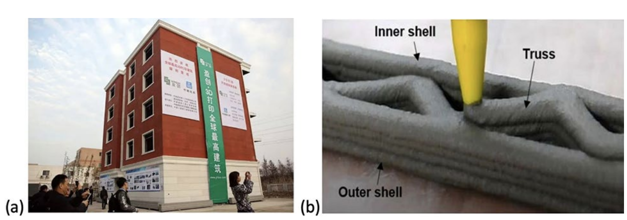

Fig. 5 A sample of concrete printing structure. **a** Five-storey 3D printed building in Suzhou, China. **b** Image showing the construction of the building using concrete printing. The building was constructed using a gantry system. It was built using prefabricated blocks that were printed offsite and assembled at the construction location (Yossef and Chen 2015)

prefabricated blocks was 10 m wide, 40 m long, and had a height of 6.6 m. In addition to the structure of the building, the printing process considered the decorative elements inside and outside the building.

- Energy consumption

  The choice of material had no significant impact on energy consumption. Furthermore, there were no built-in active or passive temperature control systems. The 3D printing process itself results in improved efficiency, which leads to a reduction in building times that eventually results in 30–70% reduction in energy consumption from traditional construction methods.
- Cost–benefit Analysis

  The estimated cost for the complete building was more that $150,000. Reports published by the company responsible for this building, WinSun, have shown that the 3D printing process saved between 30 and 60% of construction waste and can decrease production times by 50–70%. Additionally, labor costs were reduced by 50–80% because of the reduction in necessary manpower. The company claimed that the size of the printer alone allows for a 10x increase in production efficiency (Charron 2015).
- Expertise involved

  During the printing process, the company utilized a Computer-Aided Design (CAD) design template to reduce the need for additional experts. The printing software connected directly to the printing arm to automate the building process. The software was used to combine various housing elements and building structures into the design. By doing this, the design of each individual can be modified to meet different needs with- out additional cost or increased expertise and manpower.
- Structural Soundness

  The concrete mixture used to print the building blocks required additional support to ensure that the structure is sound for habitation purposes. To meet the building standards, the prefabricated blocks were stacked onsite and joined together with steel reinforcements to stabilize the structure. An insulated layer was also added to preserve the indoor temperature, reduce energy wastage, and prevent water leakage.
- Sustainability

  The building was created using a special mixture created by the company. This mixture contained recycled construction waste, glass fiber, steel, cement, and special additives. Using recycled materials during the construction process significantly reduced the need for externally sourced building materials, resulting in a construction method that is both environmentally friendly and cost effective. In traditional construction processes, construction waste is responsible for a significant portion of carbon emissions. Since the process uses standard materials, construction workers also face a reduced risk of encountering hazardous materials in the work environment.

4.2.3 3D printed house with the D-shape method

The building named, Una Casa Tutta d'un Pezzo, reimagines housing as a structure developed as a single block of concrete (Fig. 6). The entire structure was printed all at once using and off-site D-Shape 3D printer. The house was later transported to its final location at the Triennale Design Museum where it is now being displayed. The installation aimed to revolutionize the approach that designers can use to tackle emergency situations.

- Energy consumption
  The structure was built entirely out of concrete. As a result, the energy required to produce the construction materials may be comparable to a similarly sized house built using traditional construction methods. The non-use of a traditional construction procedure eliminated greenhouse emissions, energy consumption, and noise pollution required by operating heavy machinery at the construction site.
- Cost–benefit Analysis
  No official financial reports have been published for this project. We can compare, however, the cost of materials, project duration, and the labor required to build the structure with two similar structures that were built using traditional construction methods. We do this to determine whether there is a direct financial benefit to utilizing robotic 3D printing. The 3D printing process deposited concrete layers directly on-site, which reduced the cost of transporting the materials. There is less manpower required as the project was entirely built using a printer. Finally, using a D-shaped printer made it possible to construct the house in a single print within two working weeks from the start of the project.
- Expertise involved
  The design of the house was done using CAD modeling software that produced an STL file. This file was then loaded to the 3D printer, which performed the construction process by depositing concrete layers of the outer walls that subsequently formed the final house design. No additional expertise was required during the printing process. Additionally, once the house has been designed, the STL file can be used to construct multiple houses without additional design input or expertise.
- Structural Soundness
  A concrete mixture that was similar to traditional concrete was used to print the house. Since no complex geometric components were integrated into the design and due to the scale of the building, no additional structural elements had to be incorporated into the building to ensure its structural integrity.
- Sustainability
  Construction systems utilized in the building of this house were based on the stereolithography principles that allow for the construction of struc- tures of varying shapes and sizes using a particular mixture of concrete. This mixture was composed mainly of sand combined with a special inorganic reagent. Stereolithography relies on the production of parts in a layer by layer of fashion using a photochemical process in which light is used to cross link monomers and oligomers together to form a strong polymer. The final structure of the building utilized 35 m^3 of the raw concrete mixture. 90% was recovered for subsequent prints.

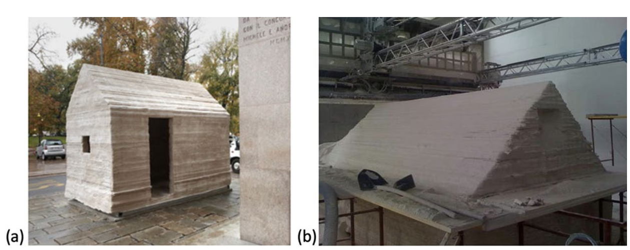

Fig. 6 Sample of a D-Shape printed structure. **a** A single-print housing concept developed in Milano, Italy. **b** Image showing the construction of the building using the D-Shape method. It was prefabricated in an offsite con- struction lab before being transported to a location where it is now being displayed (ScholarWorks et al. 2023)

4.3 Decision tree

By categorizing existing structures that were relevant to this study, and analyzing the procedures, impacts, and results of those use-cases, we formed a taxonomy that can act as a foundation for future work. In this paper, we further build on this foundation by drawing conclusions that can aid in future AEC projects. The combination of all the gathered information provides us with the ability to create a guide for individuals wishing to utilize 3D printing to develop construction projects. Based on the gathered constraints, as well as the considerations that go into selecting a method, we created a decision-making flowchart to ease the planning process (Fig. 7). The flowchart streamlines the process of choosing the most appropriate 3D printing method based on the available options and the nature of the printed structure through a series of yes or no questions.

It is worth noting that the decision-making flowchart is not a conclusive method of evaluating the construction

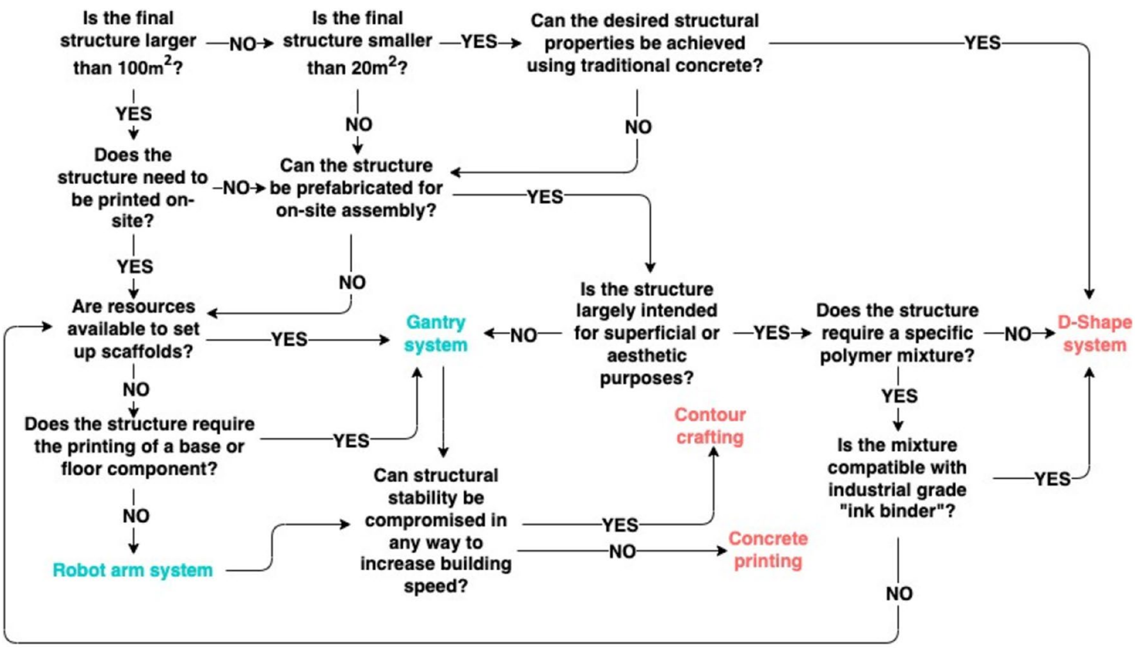

Fig. 7 Decision-making flowchart used to select the most appropriate 3D printing method based on the available resources and taxonomy

method that is most applicable to the situation. Instead, it presents a mode through which individuals, teams, and companies aiming to utilize additive manufacturing, particularly 3D printing technology, can best assess and make informed decisions regarding the existing solutions and how they meet their needs.

The 3D printing methods that can be used in construction will depend on many factors. These include but are not limited to: the resources available to the construction team and the building guidelines and processes that must be followed. These factors are dependent on the use case and are not generalizable. Thus, the way the decision-making flowchart has been designed allows teams to answer questions as they relate to their particular situation. The purpose of the flowchart is to guide people through this process in a streamlined manner with the goal of reducing the adoption barrier of these new methods.

It is also important to mention that the methods mentioned in the taxonomy and the decision- making flow chart in this paper were intended to provide a comprehensive outlook of the technology and how it has been used. They do not offer an all-inclusive account of the said technology and all the applications where it has been utilized. While these methods provide an insight into what has generally been most used, previous studies have experimented with combinations of the methods to improve efficiency and streamline production. Collaborative mobile robots are one example of such an application.

In one implementation of collaborative mobile robotic technology, researchers in Singapore Center for 3D Printing, Nanyang Technological University used multiple small robotic arms to construct a wall that was larger than the reach of each robotic arm. Together, the robots were able to build a structure that was 1.86 m long, 0.46 m wide, and 0.13 m high (Zhang et al. 2018; Izard et al. 2017). This technique shortened the time need to print the structure and addressed the restriction of the limitations in the working envelope. However, the process required more complex calculations and simulations to avoid collisions and printing failures.

In another implementation of collaborative robotics, a team of researchers from Catalonia's Institute of Advanced Architecture assembled a team of mini robots to create the external frame of a building (Zee et al. 2017). The robots spray a variety of materials that dry and harden over time to encase the structure in a tough skin. The team of wheeled

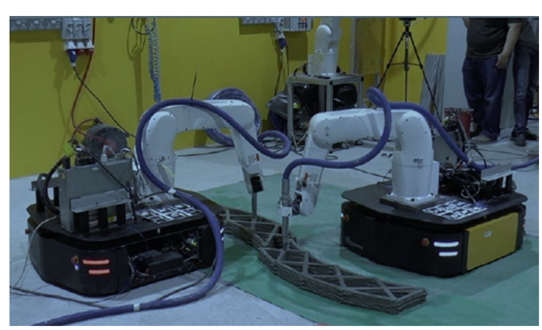

Fig. 8 Collaborative mobile robots building a wall structure (Zhang et al. 2018)

remotely controlled robots consisted of robots that were responsible for building the foundation layer at the base. These were then followed by climbing robots that were able to add additional layers and build higher levels on top of the foundational layer (Fig. 8).

5 Conclusion

This paper presents a study of the latest methods and advances in robotic 3D printing in the AEC field. The methodology of robotic 3D printing was illustrated alongside the hardware and the software used in the process. Moreover, a new way to categorize the robotic 3D printing in the AEC industry was introduced and demonstrated. Based on that information, we constructed a decision making chart that considered common structural considerations for 3D printing.

Additive manufacturing in the AEC industry offers a solution to many of the problems that are found in the industry today. This comes as we seek novel methods for increasing sustainability and reducing the carbon footprint of new buildings. Moving forward, 3D printing can be used to support the building of resilient, sustainable building and cities as they continue to become the standard. Furthermore, it is lucrative from a business standpoint as it will lower the costs of the conventional methods, increases safety, and reduces human error in the construction site (Buswell et al. 2007).

The strengths and limitations of 3D printed buildings have also been considered. The simplicity and low financial and time cost associated with the construction process enables such buildings to be far more modular than traditionally constructed buildings, which would otherwise require entire teams to be assembled and significant time to be accounted for prior to adding any extension. The process has its limitations. For example, it is far more difficult to use current 3D printing methods to alter the interior of a building after it has already been methods. Aesthetics remains another point of contention when discussing widespread adoption. 3D printers construct structures in the form of layers, and at present 3D printed buildings retain this aesthetic property even when completed. This remains a subjective matter that may not appeal to many. Moving forward, this property of 3D printed houses will have to undergo the scrutiny of public opinion before it is widely accepted. Alternatively, a solution for this will need to be developed with the emergence of more modern tools. Finally, doors, walls, and roofs present a significant limitation for 3D printed structures at present. In most of the cases discussed in the paper, these elements were retrofitted or added later after the walls had been printed. It is possible that an efficient system for this could be developed over time. While the technology remains in its infancy, no widespread solutions have been established yet.

The paper utilized a qualitative analysis method based on five distinct factors that reflect essential information about the future of 3D printed buildings, and their capacity to solve future problems in an efficient and cost-effective way. In the future, it is possible to use this to develop a quantitative method for objectively standardizing the impact of a certain project. While such a task is beyond the scope of this paper, future projects, may wish to pursue this objective as it would provide significant benefits to anyone attempting to build lasting projects that leave an impact. Such a grading method may not have to be limited solely to 3D printed buildings as well and can be used to evaluate any similar projects.

This paper focused on the procedures related to implementing 3D printing methods in building construction and the hardware associated with it. While an in-depth analysis of the existing software falls outside the scope of this study, this paper provided an overview of the existing automation procedures that can streamline building design and printing processes. Considerations of the software, and its suitability to each individual case should be given during the implementation of relevant applications. Future studies may consider performing a thorough analysis and categorization of the existing software, how it has been used in the past, and how it can be improved to meet the demands of AEC projects that aim to utilize additive manufacturing more broadly in coming years.

While this paper focused on the 3D printing of concrete, most 3D printed buildings are hybrid constructions in which 3D printed elements are combined with traditional materials to create a final structure. We note that the paper does not view 3D printing as a replacement for traditional methods, but as more of a new process that could improve key elements of the construction process while reducing the time, effort and cost required at certain stages of construction.

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