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REVIEW

Analysis of 3D printing techniques for building construction: a review

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Abstract

3D printing is a rapidly developing industry, which allows producing objects of different size using additive manufacturing technologies. Large-scale 3D printing has the potential to revolutionize the construction industry by making housing construction faster, more affordable, and sustainable. It allows for the creation of unique and customizable designs directly on-site with high precision. This study starts with an overview of the four 3D printing technologies that are used for building production. The main technical parameters, such as physical dimensions, printing speed, materials and technological limitations are identified and compared. The second step contains the analysis of the 3D printed buildings, including their design, size, construction time, and the need to use any additional structures. In conclusion, the different types of 3D printers and 3D printed houses are evaluated to find the most advanced and efficient technical solutions.

Keywords Additive manufacturing · 3D printer · Digital fabrication · Building construction

1 Introduction

The technology of 3D printing (3DP) is diverse in the ways it is applied. Additive manufacturing, known as 3D printing, is available not only for professional work and industry, but also for the public (Dunn 2012). The 3D printers use different materials depending on the technological processes. The small-scale 3d printers utilizing plastic filament are affordable and widely used for hobbies and digital art. In 1981 Hideo Kodama invented layer-by-layer 3DP using photosensitive resin polymerized by ultraviolet light. Hull obtained the first patent for this technology in 1987, after the SLA-1 development of the stereolithography prototype (Huang et al. 2020). During the next decade, different methods of the 3DP, such as Fused Deposition Modelling, and Selective Laser Melting and Sintering. The first small 3D printer became commercially available in 2006. After 2010 3DP became affordable and started to be used worldwide. 3DP is the technology that completely changed the organization of industrial manufacturing processes (Parupelli and Desai 2019). The industry paradigm shifted towards the on-site production of personalized objects based on the local needs (Paoletti and Ceccon 2018). Currently, 3D printers are used in various industries, such as manufacturing, architecture modeling, food, medicine, fashion, and aircraft industry. There are seven 3D printer types, which are the directed energy deposition, binding jetting, materials jetting, materials extrusion, sheet lamination, VAT photopolymerization and powder bed fusion (Flynn et al. 2016). Each technology is highly specific and is used in different fields of production; therefore, they cannot be compared with each other (Shahrubudin et al. 2019). The IPOS study (IPOS 2019) demonstrates the growing interest in companies specialized in 3D printing of buildings and the increasing number of inventions in this field.

The first 3D printer capable of producing 1:1 scale building was presented by Khoshnevis in 2006. In 2014 'DUS Architect' explored the new way to build by printing using plastics. Concrete 3D printing was also applied in the USA and in China. In 2014 WinSun constructed the villa using the prefabricated elements, which were 3D printed at the factory (Wu et al. 2016). The same manufacturer produced 10 houses within one day using the 150 m long 3D printer (Feng and Yuhong 2014). In 2015 a bridge was produced using a robotic arm. In 2016 MIT printed a dome using the robotic arm, which poured concrete on a circular path (Chandler 2017). The first fully 3D printed settlement of 50 houses was completed in 2020 in Tabasco, Mexico (Schuldt et al. 2021). The timeline for the development of large-scale

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3D printers is shown in Fig. 1. 3DP did not reach its maximum application potential, as it is currently used for the manufacture of single buildings (El-Sayegh et al. 2020). The ongoing research is expanding in the multiple dimensions from the increasing of the building size and application of the new materials, towards the theoretical investigation of the possibilities of 3D printing of the bricks (Sacco and Moon 2019) and habitats in the space (Roman et al. 2020). The Relativity Space Company is developing the Stargate 3D printer, aiming to be able to produce the entire rocket ships (Palmer 2020).

Use of the 3DP technologies at the construction site brings multiple benefits. It reduces material waste and transportation costs since all building components are produced on site (Shakir 2019). The construction errors are minimized due to the use of the automated processes (Adedeji et al. 1299). Some technologies allow using the locally sourced materials, such as clay and mud, however for the better durability of the building, reduction of the material needs and machine working hours can be achieved with the use of the thinner structural elements and lightweight fiber-reinforced concrete (Inozemtcev and Duong 2019). Reduction of concrete use reduces environmental impact (Abdalla et al. 2021). The problem of additional reinforcement is solved by using robots to insert steel bars during the printing process (Yin et al. 2021). 3DP is an efficient tool for the production of nonlinear geometry and curvilinear surfaces, which allows overpassing the limitations of the traditional regular design (Sakin and Kiroglu 2017). The houses are adaptable for the needs of residents and can reflect their personal desires (Mahdi 2021). Some of the 3D printers utilize locally sourced raw materials with low embedded energy and CO_2 emissions, such as clay, earth, straw and husk, which makes them more sustainable in comparison with concrete construction (Hager et al. 2016). Fewer number of trained workers areengaged at the site, which decreases the labor costs in developed countries (Elfatah 2019). Multiple studies have noted that with the use of 3DP, the house can be completed significantly faster than using conventional methods (Hager et al. 2016) (Shakir 2019; Pandit and Kumari 2021).

The application of 3DP in construction has multiple limitations. The main is the building volume limited to the size of the printer. Further extensions are possible only with the relocation of the machine. For better structural performance, 3DP requires using the specific flowable cement mixture (Hussein 2021). Most of the 3DP are used to construct only the self-supporting load-bearing exterior and interior walls, therefore the further installation of the building services should be considered at the design stage (Romdhane and El-Sayegh 2020). Roofs and slabs are added at the final stage of construction and constructed using traditional techniques and materials (García-Alvarado et al. 2021). The 3DP volumes have a poor finishing quality of the surfaces with the visible texture of the printing layers (Ali et al. 2022). 3DP process has the high dependency on the environmental conditions of the construction site, such as wind speed, air temperature, slope inclination (Niemelä et al. 2019). At the current level of development, it is difficult to achieve standards of seismic resistance or fire resistance (Pessoa and Guimarães 2020). Specific standards related to the quality of the assessment of 3DP structures have not yet been established (Ortega et al. 2020). 3DP requires skilled human resources to obtain sufficient knowledge both in masonry and in digital fabrication (Hossain et al. 2020). The 3DP equipment is not commonly used, it requires additional transportation time and cost due to the long delivery distances. Developers are

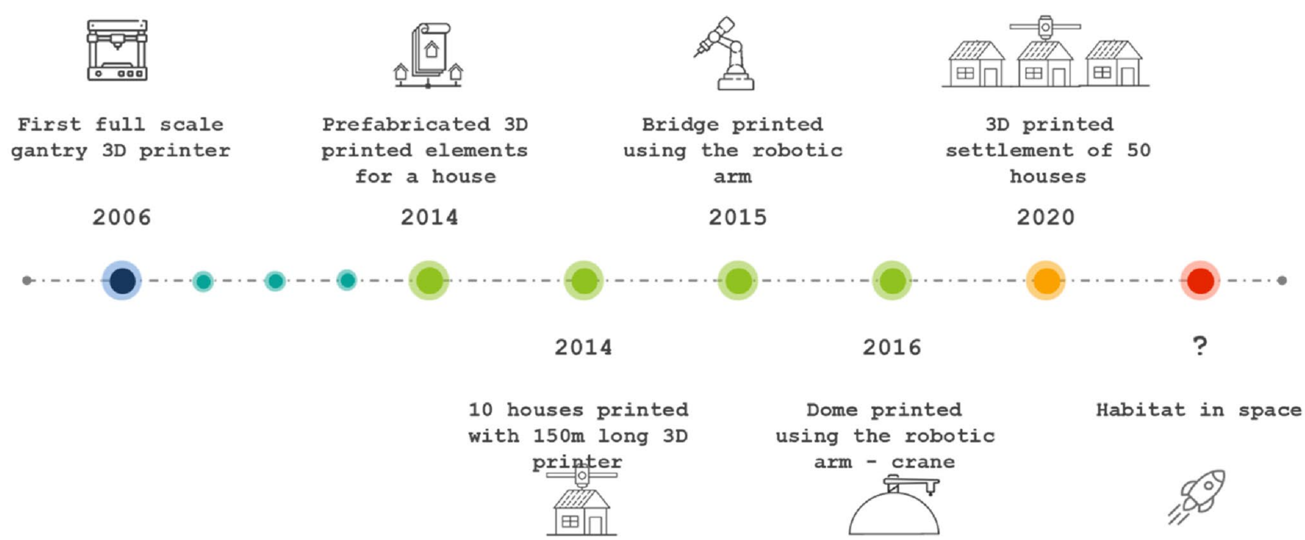

Fig. 1 Evolution of the large-scale 3D printers

not familiar with this new technology and have to be convinced and motivated to apply it on site (Aghimien et al. 2020). The 3DP in construction is associated with the high initial investment costs, and it is assumed to be cost-efficient at the time span of more than 8 years (Olsson et al. 2019). Based on the results of potential residents' survey, the idea of the 3D printing is called futuristic, exciting and advanced, but the potential users need proof of structural stability and durability of the building (Ariyan et al. 2020) and are not convinced to live in such a building for a long time.

2 Methodology

The research (Fig. 2) starts with an overview of the 3D printers, which are currently used for building construction. There are four main typologies chosen, such as gantry, cable-driven, robotic arm and hybrid printers. Ten manufacturers have been selected, currently taking the leading positions in construction and research. The specifications, such as physical dimensions, technical requirements, printing speed, accuracy, construction materials, and cost of the 3D printers, are collected. This information is provided as open access by manufacturers and retailers. Further, the 22 realized projects of the 3DP buildings were selected. The case studies are classified according to the type of 3DP that was used for the construction. There are found the physical dimensions of the building, the printing time, the construction materials, the design features and the necessity of use of the additional structural elements. The comparative analysis continues with the evaluation of the performance of the selected 3DP by the set of parameters, such as price, speed, construction volume and need for the operators. The concluding overview of the 3D printers allows one to select the most efficient solution based on the specific construction needs.

3 Technological solutions for the large-scale 3D printers

This section aims to investigate the technical parameters of the large 3D printers which are used for building construction. 3D printers are classified according to technological solutions. Multidimensional evaluation of 3D printers is based on their performance in terms of printing speed and printing volume, accuracy, availability, affordability, and

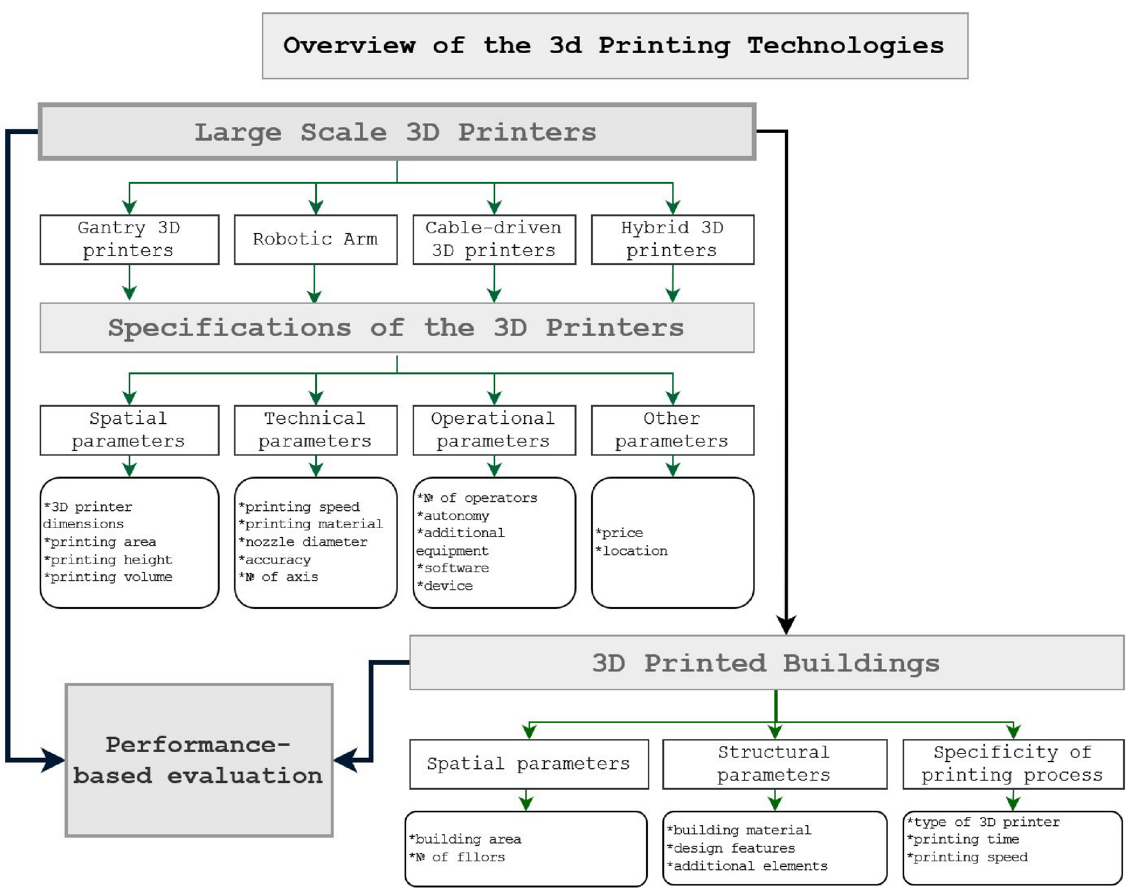

Fig. 2 Research methodology

the need to train operators to use additional software and devices.

3.1 Gantry 3D printers

The Gantry 3D printer is the most common 3DP technology. It has a cuboid-like frame, which allows the actuator to move in the X, Y and Z directions. The first trial to print a building by pouring concrete was conducted by Khoshnevis in 2001 (Labonnote et al. 2016). An experimental printer using Taylor–Ball clay was created to test the technology on a small scale (Khoshnevis et al. 2001). The printer head included vertical and horizontal trowels to flatten the printed layers and to create a smooth surface of the wall (Hwang and Khoshnevis 2005). In addition, the printer was scaled up for on-site building construction. Figure 3 shows the 3D gantry printers most commonly used, which are Vulcan ll, BOD2 and BetAbram P1.

Icon used Vulcan II to construct the walls in the neighborhood for homeless. Vulcan II can be used in remote areas, where traditional construction is highly expensive due to lack of materials, weather conditions, and lack of power. This printer can be controlled remotely using the BuildOS smartphone application. The construction material uses a special mixture of concrete, which can withstand extreme weather and natural disasters (Palmer 2020). The nozzle diameter is 50 mm. The 3D printer has dimensions of 14.2 m length, 11.1 m printing width, and 4.7 m height, with 3.2 m maximum printing height. The printing dimensions are limited to one floor and the maximum building volume is 57.46 m^3 (ANIWAA 2019). The printing length is infinite, since the 3D printer can move on rails. The required power is 230/240 V single phase, and the printing speed is 12.7–25.4 cm/sec (ICON 2018). It can be operated by 4–6 people (Boissonneault 2019). The price of this printer is approximately € 409.230.

BOD2 is the most popular 3D printer produced by a Danish company. It has customized dimensions with width up to 14.6 m, length up to 50.52 m and 8.1 m height, which allows to print the 2-floor height buildings. Its printing speed is 1 m/s, making it the fastest in the world (COBOD 2020). It uses flaps at the two sides of the nozzle, which flatten the layers and make wall surfaces smooth both inside and outside. The width of a single layer ranges 30–300 mm and the height is 10–40 mm. The nozzle is flexible with a 20–50 mm diameter. The print volume is 6012 m^3 (ANIWAA 2018a). The printer is waterproof and can resist wet environments. It uses the COBOD Slice software, and it requires two operators to work. The required power is 400 V, three-phase power supply. The price of this printer is € 272.820.

BetAbram P1 is produced by a Slovenian company (ANIWAA 2017c). P1 is one of the three models offered by this company, and it is specified for construction (Jakupovic 2015). P1 has a concrete length of 16 m, uses a mixture for the printing, and requires stopping after every 25 cm of added height to wait 5–6 h until the material dries. The diameter of the nozzle is 40 mm. The maximum building volume is 328 m^3 and the printing speed is 50 cm/s. Betabram needs 4 kW to run and 2 operators for the process. It uses Betabram software for operation, which is modified CNC software. The price of the P1 model is around € 32.000.

3.2 3D printers using the robotic arm

The robotic arm is widely used in the manufacturing industry, as it helps reduce the labor force and complete many tasks in a short time. The mechanical arm mounted at a single point moves along the circular path and precisely completes the assigned task. 3D printers based on the robotic arm pour concrete on the defined track. They are equipped with the set of sensors that can control material properties, environmental conditions, robot movement, and feed rate (Al Jassmi et al. 2018). 3DP robots can perform more accurate tasks and have a higher degree of freedom but are strictly limited by the size of the printable area and require the higher initial investments (Paul et al. 2018). Large-scale structures can be produced with the coordinated use of multiple robot arms installed on mobile platforms (Puzatova

Fig. 3 Vulcan ll (left) (M3 Design 2019), BOD2 (middle) (COBOD 2016) and BetAbram P1 (right) (Jakupovic 2015) gantry 3D printers

et al. 2022). Figure 4 shows the MAXI printer, CyBe RC 3Dp and Apis Cor printer.

The MAXI Printer is produced by the French company Constructions-3D and is able to print the buildings up to one-story height. It operates within a cylindrical volume with a diameter of 9.5 m and a height of 3.3 m. In case if building area is larger, this printer can be moved to another location (Stevenson 2022). It uses concrete, which is poured through a nozzle with a diameter of 20–50 mm. The maximum printing area is 116.8 m^2, and the maximum built volume is 385 m^3 (ANIWAA 2017d). MAXI Printer has 10 mm accuracy. The printing speed is up to 30 cm/s. The automated pumping system is separated from the printer. 2 workers can manage all the tasks of installation, printing, and cleaning (Constructions-3D 2017). The process is controlled by the C3D Slicer Software. The price of this printer is about €495.168.

CyBe RC 3Dp is a 3D robotic arm printer produced by the CyBe construction company, located in the Netherlands (CyBe 2017a). CyBe offers five different types of 3D printers, which can be fixed, mobile, track-based, gantry, and gantry with the robot. CyBe RC 3Dp is able to change location because it is mounted on a crawler. The printing material is a custom CyBe Mortar mixture. To pour the material, this printer uses a 25.4 mm diameter nozzle, and can print at 50 cm/s speed (ANIWAA 2018b). Since this printer moves autonomously, there are no limitations on the width and length of the structure. The maximum building height is 3.5 m. For a single location, the maximum printing area is 32.2 m^2 and the built volume is 112.5 m^3. The printer can be operated by two people. The CyBe Artysan slicing software is required for control. For the modeling phase, a CyBe Chysel plug-in for Rhinoceros can be used. The price of CyBe RC 3Dp is €186.427.

Apis Cor is produced by the US-based Apis Cor Company. It has a maximum printing radius of 5.5 m, and it can print structures with height up to 3.2 m (ROBOTPLACE 2019). The maximum printing area is 95 m^2, and the built volume is 295 m^3. The company proposes to use the regular mixture of concrete with small aggregate. Apis Cor has a printing speed of 16.7 cm/s and an accuracy of 0.2 mm. 2 workers are needed to operate this printer. The 3D printer is easy to move because it is mounted on a remotely controlled crawler. It utilizes the Apis Cor Software that requires a tablet mounted on the external equipment with joysticks. The printer is easily transportable to any construction site with a regular truck. Apis Cor company has estimated, that the cost to print a 1 m^2 wall is approximately €25 (ANIWAA 2017a). The cost of this printer is not displayed by the company, it is provided via leasing.

3.3 Cable-driven 3D printers

In the cable-driven 3D printers the printing head is hung from the framing structure with cables. The minimum set of 4 cables and standard of 8 cables move the printing head in x, y, and z directions (Pott et al. 2012). BigDelta WASP 12MT (Fig. 5) is an example produced by the Italy-based WASP company (ANIWAA 2017b). This 3D printer uses on-site materials, such as soil or mud mixed with long fibers, such as straw. Its base is a hexagon inscribed in a circle with a diameter of 7 m, and the 12 m height structure allows the production of 3-story buildings (WASP 2015a). It can print a structure with a footprint of 23.4 m^2 and a maximum volume of 280.8 m^3. BigDelta WASP 12MT can print with a speed of up to 40 cm/s and can be operated by 2–4 workers. The cost of it is not specified due to its status as an experimental project.

Cable-Driven Parallel Robot (CDPR) is an experimental 3D printer that is designed to produce concrete structures (Tho and Thinh 2021). The robot steel frame has footprint dimensions of 3.5 × 5 m and height of 2.8 m, while the work area is limited to 3 × 2 × 2 m. Tho and Thihn specify that the dimensions of the frame can be easily increased (Tho and Thinh 2021). The concrete extruder is supported by 8 cables, and its operating speed is 4 cm/s.

3.4 Hybrid 3D printers

There are hybrid technologies that are used for building construction. Recent theoretical studies describe the swarm approach, a concept of using the multiple small-sized robots

Fig. 4 MAXI printer (left) (ANIWAA 2017d), CyBe RC 3Dp (middle) (CyBe 2017a) and Apis Cor printer (right) (ROBOTPLACE 2019) 3D printers

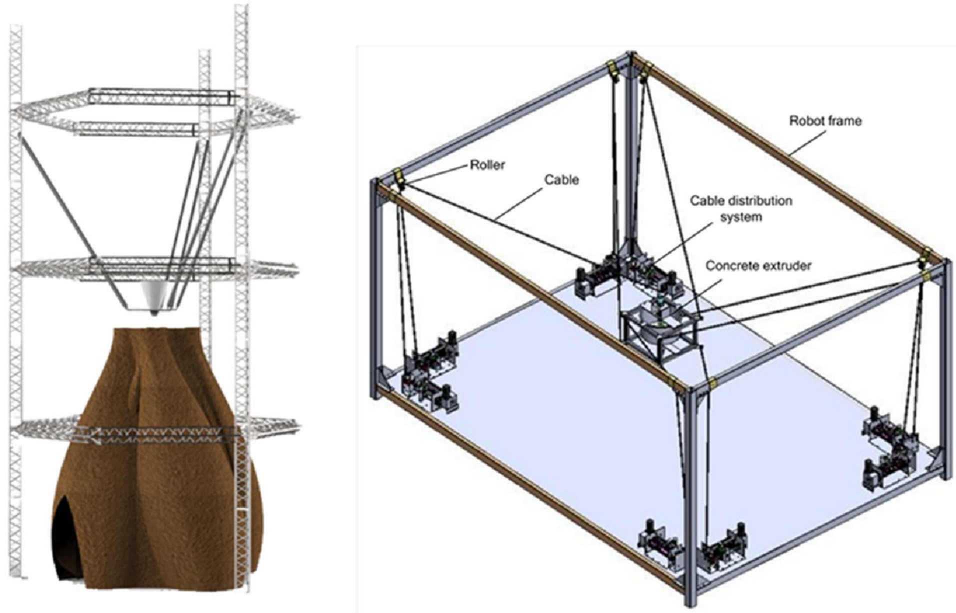

Fig. 5 BigDelta WASP 12MT cable-driven 3D printer (left) (ANIWAA 2017b) and Cable-Driven Parallel Robot (right) (Tho and Thinh 2021)

with different specializations (Labonnote et al. 2016). However, on-site there are used the solutions, which combine the features of the three main technologies, such as gantry system and a crane, or a crane with the custom printing head (Fig. 6).

The DeltaWASP Crane is fixed at one spot by the three structural elements, where the central one holds the robotic arm (crane), which pours the material (WASP 2015). WASP uses a modular system, which is a series of DeltaWASP Crane printers connected to create a hexagonal pattern (Quinn 2021), which is more efficient in terms of building speed. The DeltaWASP Crane has a printing radius of 3.15 m and a maximum height of 3 m. It can print an area of 31.2 m^2 and a building volume of 93.5 m^3. During the on-site printing it needs additional equipment, such as a mixing machine. The material is the local clay, and its application is thought to resemble the vernacular architecture (Cucinella 2021). The printing speed is up to 30 cm/s and the nozzle diameter is 18–30 mm. The operating software is provided by the WASP Company. The basic model of the DeltaWASP Crane costs €132.000.

CONPrint3D is developed by the TU Dresden in Germany. One of the main features of it is the possibility of reinforcement between the two concrete layers. CONPrint3D uses a regular concrete mixture. CONPrint3D is realized as a prototype gantry printing, but it is planned to be installed

Fig. 6 DeltaWASP Crane (left) (WASP 2015b) and CONPrint3D Crane (left) (Näther et al. 2017)

on a modified crane. This printer can print a floor with an area of 130 m^2 in one day (Mechtcherine et al. 2019). The producer stated that it can print multistory buildings. CONPrint3D has a unique printing head, which allows wide layers to be printed (Näther et al. 2017). The accuracy of the printing is less than 5 mm. For the fine filaments the printing speed is 15 cm/s, and the nozzle diameter is 20–30 mm. The section of the printing layer can be expanded till 50 × 150 mm, which allows to print the building walls using just one pass of the printing head (Mechtcherine et al. 2019). CONPrint3D uses Cura as a slicing software. The price of the CONPrint3D is not displayed, since the experiment is still ongoing.

3.5 Specifications of the selected 3D printers

Table 1 shows the general information, such as the manufacturer, location, and price of the selected 3D printers. BetAbram P1 is the most affordable gantry 3D printer, while DeltaWASP Crane and CyBe RC 3Dp are the hybrid and the robotic arm 3D printers, which belong to the middle price category. The 3DP software is usually free and available to download or included in the starter kit. However, the WASP and the CYBE 3D printers require a single purchase, or the annual subscription, which is less than 1% of the equipment price.

The spatial characteristics of the 3D printers are given in Table 2. Gantry printers use the area which is appropriate to print the single-family house. The gantry can be constructed as a fixed structure, but it is possible to install it over the rails in order to extend the printing area. For robotic arm and crane 3D printers, the building footprint is limited by a circle. CONPrint3D is an exception, since its printing head is mounted on the truck. Most of the 3D printers are limited by height, thus allowing to construct the buildings of one floor. However, BOD2, BigDelta WASP 12MT and CONPrint3D can be used for the higher buildings.

Table 1 Main parameters of the selected 3D printers

No.	3D Printer	Producer	Location	Typology	Software price, €	Price, €
1	Vulcan II	Icon	USA	Gantry	Free[1]	409,230
2	BOD2	COBOD	Denmark	Gantry	Free[2]	272,820
3	BetAbram P1	Betabram	Slovenia	Gantry	Free[1]	32,000
4	MAXI Printer	Constructions-3D	France	Robotic Arm	Free[1]	495,168
5	CyBe RC 3Dp	CyBe	Netherlands	Robotic Arm	1500 €/year	186,427
6	Apis Cor 3D Printer	Apis Cor	USA	Robotic Arm	Free[1]	N/A (leasing)
7	BigDelta WASP 12MT	WASP	Italy	Cable-driven	185	N/A (experimental)
8	CDPR	HCMC UTE	Vietnam	Cable-driven	Free[3]	N/A (experimental)
9	CONPrint3D	TU Dresden	Germany	Hybrid	Free[2]	N/A (experimental)
10	DeltaWASP Crane	WASP	Italy	Hybrid	185	132,000

[1]Included in the starter kit

[2]Available to download

[3]3D printer is at experimental stage

Table 2 Spatial characteristics of the selected 3D printers

No.	3D Printer	Width, m	Length, m	Height, m	Radius, m	Footprint area, m^2	Building volume, m^3
1	Vulcan II	11.1	∞	3.2	–	∞	∞
2	BOD2	14.6	50.52	8.1	–	737.6	6012
3	BetAbram P1	9	16	2.5	–	144	328
4	MAXI Printer	9.5	9.5	3.3	6.1	116.8	385
5	CyBe RC 3Dp	∞	∞	3.5	3.2	32.2	112.5
6	Apis Cor 3D Printer	∞	∞	3.1	5.5	95	295
7	BigDelta WASP 12MT	7	7	12	–	23.4	280.8
8	CDPR	3	2	2	–	6	12
9	CONPrint3D	∞	∞	–	–	–	–
10	DeltaWASP Crane	6.3	6.3	3	3.15	31.2	93.5

In Table 3 is given the information related to the printing process. The majority of the 3DP use concrete, while CyBe RC 3Dp uses the custom mortar, Vulcan II uses lavacrete and the WASP family 3D printers utilize locally sources materials, such as long fiber mixture and clay. BOD2 is the fastest 3D printer with the speed of up to 100 cm/s; BetAbram P1 and CyBe RC 3Dp demonstrate the speed of 50 cm/s, BigDelta WASP at 40 cm/s, after that the MAXI Printer and DeltaWASP Crane score 30 cm/s. The slowest are Vulcan II with 25.4 cm/s, Apis Cor 3D Printer with 16.7 cm/s, and CONPrint3D with 15 cm/s printing speeds. The nozzle diameter is similar for all the case studies except the CONPrint3D, which is designed to print one layer of the wall in one pass. Accuracy is applicable only for robot-based solutions and CONPrint3D, which uses the manipulator. These printers have the higher number of axes, which allows producing complex objects.

Information on 3DP operation and transportability is given in Table 4. The BOD2, BetAbram P1, MAXI Printer, CyBe RC, and Apis Cor require two people to operate during the printing process, while BigDelta WASP 12MT, CONPrint3D, CDPR, and DeltaWASP Crane require 2–4 operators, and Vulcan II 4–6 operators consequently. Vulcan II, CyBe RC, Apis Cor and CONPrint3D are able to move autonomously due to the use of rails or crawlers. All 3DPs must use additional equipment to prepare the concrete mixture. Each producer offers specific software that allows the printing process to be controlled.

4 3D Printing for the building construction

This section explores the design, spatial parameters, structural solutions and the construction time of the realized 3DP buildings. The Netherlands, USA, China, Spain, UK and Russia take the leading positions in the application of the 3DP for building (Pan et al. 2021). The buildings are classified according to the type of 3DP that was used during construction. The study includes 9 buildings produced with the use of gantry 3DP, 8 cases produced by the robotic arm, one case for the cable-driven 3DP and 4 cases for the hybrid 3DP.The evaluation of the case studies includes the building

Table 3 Materials and printing specifications of the selected 3D printers

No.	3D Printer	Material	Printing speed, m/s	Nozzle diameter, mm	Accuracy, mm	No. of axis
1	Vulcan II	Lavacrete	0.127–0.254	50	–	3
2	BOD2	Concrete	0.25	20–50	–	3
3	BetAbram P1	Concrete	0.5	40	–	3
4	MAXI Printer	Concrete	0.3	20–50	10	5
5	CyBe RC 3Dp	CyBe Mortar	0.5	25.4	0.15	6
6	Apis Cor 3D Printer	Concrete	0.167	–	0.2	5
7	BigDelta WASP 12MT	Long fiber mix	0.4	–	–	4
8	CDPR	Concrete	0.04	–	10	6
9	CONPrint3D	Concrete	0.15	30–20; 50–150	5	5
10	DeltaWASP Crane	Clay	0.3	18–30	–	3

Table 4 Operational requirements of the selected 3D printers

No.	3D Printer	Nr. of operators	Autonomous movement	Additional equipment	Software	Device
1	Vulcan II	4–6	YES	YES	BuildOS	Smartphone
2	BOD2	2	NO	YES	COBOD Slice	Laptop
3	BetAbram P1	2	NO	YES	Betabram	Laptop
4	MAXI Printer	2	NO	YES	C3D Slicer	Laptop
5	CyBe RC 3Dp	2	YES	YES	CyBe Artysan	Laptop
6	Apis Cor 3D Printer	2	YES	YES	Apis Cor	Custom tablet
7	BigDelta WASP 12MT	2–4	NO	YES	WASP	Laptop
8	CDPR	2	NO	YES	Trust-Region-Dogleg algorithm	Laptop
9	CONPrint3D	2–4	YES	YES	Cura	Laptop
10	DeltaWASP Crane	2–4	NO	YES	WASP	Laptop

area and height, the shape morphology, the materials used, the additional building elements and the construction time.

4.1 Buildings constructed with the gantry 3D printer

The buildings, which are constructed using the gantry 3DP, are shown in Fig. 7. All buildings have conventional designs, are similar in size and require the use of additional structural elements after the completion of the 3D printing process.

The low-income neighborhood of 50 houses in Tabasco, Mexico, is built using single-story units of 46.5 m^2 by Vulcan II (Delbert 2019). The walls are printed in 24 h (Bendix 2019), but the porch, terrace, and roof are added afterward. The construction cost is estimated to be approximately € 3700 per unit. The Micro-Cabin is located in Amsterdam, Netherlands. It is printed using the XL 3DP, which utilizes the recyclable bioplastic, and its area is 8 m^2 (Frearson 2016). It includes the 3D printed bed and a bathtub (DUS Architects 2016). The design of this cabin is nonlinear, and the bioplastic walls are self-supporting (Penn 2014). The 90 m^2 two-story house was built by BOD2 in Westerlo, Belgium, in 504 h (Carlson 2020). The slab and roof are conventionally constructed using steel and wood. The manufacturer envisions that in future this house can be printed in 48 h, and it can exceed the two floors height. The settlement constructed by the Vulcan II in Austin, Texas is composed by the 46.5 m^2 single floor houses (ICON Team 2019), which have been printed in 27 h each. The houses are conventionally designed, and the pitched roof is completed after finishing the printing. The building material is lavacrete (ICON Team 2020), and the cost of each building is € 3700. The two-story concrete house in Bochum, Germany, is 3D printed by BOD2 for a total of 100 h spread over 10 months of construction time (Lamperti 2021). Its area is 160 m^2 and reinforced concrete slab and a flat roof are added

Fig. 7 (1) Tabasco settlement (Bendix 2019), (2) Micro-Cabin (Frearson 2016), (3) Westerlo house (Carlson 2020), (4) Austin settlement (ICON Team 2019), (5) Beckum house (PERI 2021), (6) House in Virginia (CNN 2021), (7) Dublin residence (COBOD 2022b), (8) Social house in Muscat (COBOD 2022a), (9) School in Malawi (COBOD 2021), (10) Luxury Cottage (Kira 2015)

afterward. Some interior elements, such as the bathtub, were also printed. The company claimed that it takes 5 min to print the 1 m^2 of the double skin wall (Madeleine 2021). The walls of the single story 111.5 m^2 house built by the BOD2 in Virginia, were completed in 12 h, and the roof and porch were added after the printing was finished (Smart 2021). It is made with a concrete mixture that withstands harsh climate conditions. The three-story residential unit in Dublin, Ireland, has an area of 430 m^2 (COBOD 2022). The printing is completed by the BOD2 within 288 h. Additional elements include slabs, façade finishes, and a roof. For the single-story social house in Muscat, Oman, BOD2 used standard concrete without additives. The 190 m^2 house includes 3 bedrooms and bathrooms, a kitchen, a living room and a space for guests (COBOD 2022). This building was built in 120 h. Subsequently, a roof slab was added (Hanaphy 2022). Another building of the BOD2 is the first 3D printed school, which is located in Malawi. It is a single-story building with the area of 56 m^2 (Everett 2021). The printing was finished in 18 h, and the roof was constructed using the conventional techniques (COBOD 2021). The 1100 m^2 luxury villa was built in China in 24 h using entirely the prefabricated concrete elements. In addition to the basic elements, the manufacturer produced decorative details (Kira: Exclusive 2015).

4.2 Buildings constructed with the robotic arm

The eight case studies are printed using the robotic arm (Fig. 8). There is a large variety in designs and in construction methods. The buildings are fully or partially constructed on site, as well as assembled using prefabricated 3D printed details.

The single-story 94 m^2 house located in Eindhoven, The Netherlands (Parkes 2021a) is constructed by assembling the wall parts, which were 3D printed by Weber Beamix at the factory (WeberBeamix 2018). These pieces were transported and mounted on the foundations. It took 120 h to print all the pieces (Boffey 2021). After the printed elements are settled, the roof is traditionally constructed. Three cabins with an area of 20.7 m^2 were printed in Colorado, using the SCARA 3DP. The construction material is locally sourced adobe (Rael et al. 2020). During the construction process,

Fig. 8 (1) Eindhoven house (Parkes 2021a), (2) Casa Covida (Block 2021), (3) Dubai municipality (Harrouk 2019), (4) Dubai drone laboratory (CyBe 2017b), (5) Toilet units (CyBe 2020), (6) House in the Netherlands (De Vergaderfabriek 2017), (7) House in Saudi Arabia (CyBe 2030), (8) House in Russia (Grašytė 2017)

an inflatable roof was used to protect the buildings from rain (Fratello 2021). The largest 3DP building of 640 m^2 is located in Dubai, UAE, and functions as a municipality (Block 2019). To reinforce the printed walls, steel bars were used (Harrouk 2019). Apis Cor 3DP was moved to different locations due to the limitation of its maximum radius. The slab and the roof were built using traditional methods. A Drone Laboratory was constructed in Dubai by the CyBe RC robotic arm in 504 h. This single-story organic building is made of concrete mixture (CyBe 2017b). Its area is 168 m^2, and the walls are printed separately and then mounted on site. The roof is constructed using conventional methods (Clarke 2017). Another building printed by the CyBe RC is located in Japan. It includes two toilet cabins with the total area of 16 m^2 (CyBe 2020). The printing time was about 60 h. During construction, steel bars were used as reinforcement and the roof was added later. The 100 m^2 one-story commercial building is planned to be built in 240 h in the Netherlands by CyBe RC (De Vergaderfabriek 2017). Its shape of it is organic, and the roof is projected to be printed (CyBe 2019). CyBe RC printed the 80 m^2 modular house located in Saudi Arabia in 168 h (CyBe 2018). The walls of this building are modular, and the roof was made later on site. The single-story house located in Russia by Apis Cor has an area of 37.2 m^2 and was printed in 24 h (Grašytė 2017). Its estimated cost is €10.150, which is affordable compared to conventional houses. The roof is constructed after printing is done.

4.3 Buildings constructed with the cable-driven 3D printer

There are a limited number of buildings constructed with the use of cable-driven 3D printers. Figure 9 shows the experimental 50 m^2 single-story house built by BigDelta WASP 12MT in Italy in 24 h (Moretti 2017). It is made using a mixture of lime, sand, dirt, and straw and has a custom roof composed of glass and wood (Mingorance 2021).

4.4 Buildings constructed with the hybrid 3D printer

The four buildings printed using hybrid technology have a non-linear organic form and ornamented walls (Fig. 10). The combination of the different technologies is experimental, and the cases are used rather as prototypes and then as residential units.

Located in Italy, the TECLA house has a dome-like shape, which is constructed by the DeltaWASP. TECLA is made up of two volumes one floor high. Its total area is 60 m^2, and it requires 200 h to be printed (Parkes 2021b). The materials used for the construction are local clay and straw. Gaia project by DeltaWASP Crane is a small house

Fig. 9 House in Italy (Mingorance 2021)

built with clay mixed with other biomaterials, with an added timber roof (Jordahn 2019). The straw is used as an insulation material placed in the voids inside the walls. Its area is 30 m^2, and it requires 100 h for printing (Surfaces Reporter 2021). Its construction cost is estimated at € 900. The Dior fashion store located in Dubai, UAE, is made up of pavilions, which are installed on a wooden platform. The total area of the store is 80 m^2, and the total printing time is 120 h (Mikahila 2021). Another building printed by the DeltaWASP Crane in 50 h using the local biomaterial is located in Germany (Lazzari 2021), and it functions as a pavilion for the 75th anniversary of the land of Hesse (Stackpole 2021). It has an organic shape and an area of 16 m^2. The additional elements are the wooden roof with a skylight.

4.5 Specifications of the 3D printed buildings

The general information, such as building function, building area, number of floors, design features, building materials and additional structural elements, is summarized in Table 5.

Most of the buildings are residential, including 13 houses, 2 cabins, and a shelter, while the others have commercial and administrative use. The area ranges from 8 to 640 m^2. Most cases are one-story high, but there are examples of two- and three-story buildings. By the design, the buildings can be separated into two categories. In conventional buildings, the 3DP is used to construct the exterior and interior walls, while the slabs, porches, and roofs are completed using the traditional technique. In organic buildings, the applied complex geometry, such as curvilinear walls and domes, allows one to complete the entire building using the 3DP. 13 cases are built with the use of concrete mixture, 2 with lavacrete, 1 with bioplastics, and the rest utilize natural materials such as clay, adobe, and mud.

In the Table 6 is given the information, which is related to the specificity of the 3DP process. The building speed

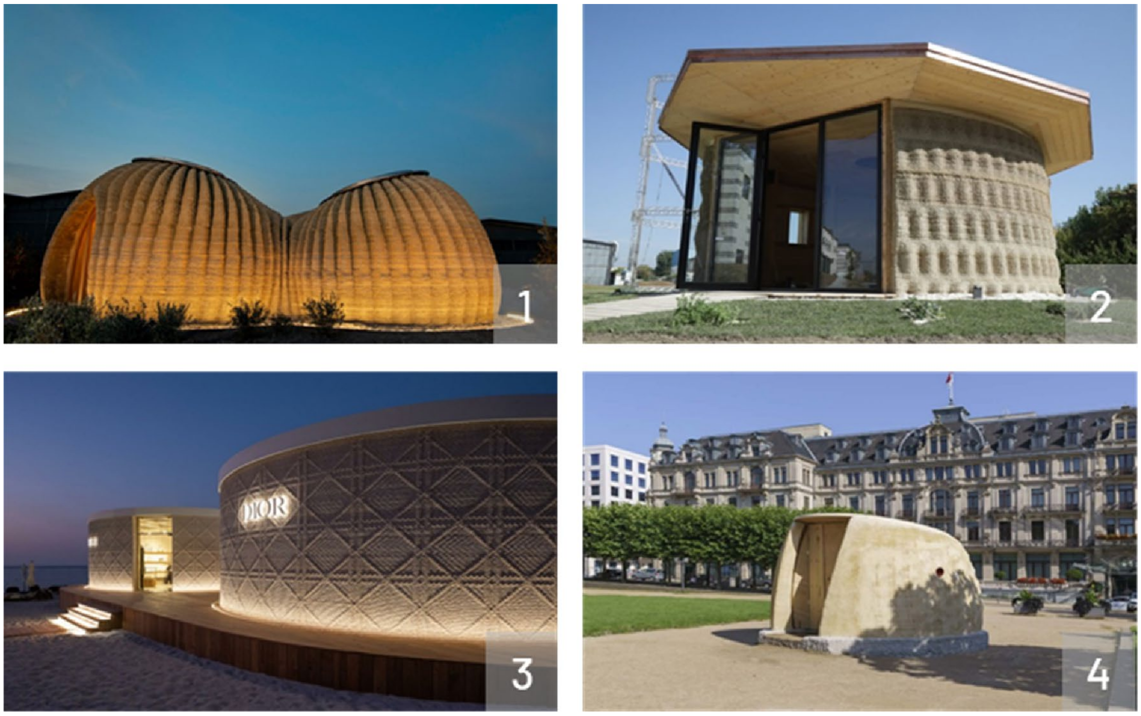

Fig. 10 (1) TECLA house prototype (Parkes 2021b), (2) Gaia house (Jordahn 2019), (3) Dior store (Mikahila 2021), (4) Hesse Sculpture (Lazzari 2021)

depends on the specificity of the building design, position of the walls, complexity of shape, presence of the vaults and domes, and necessity to print the furniture elements, therefore the performance may change. The best result is demonstrated by the BOD2 and the CyBe RC. The DeltaWASP crane and the robotic arm-based 3DP are slower, than the gantry printers. The fastest on-site is registered for two houses built by prefabricated elements, however in this case the on-factory production time should be considered.

5 Discussion

During the last decade the use of additive manufacturing technologies for building construction developed from the experimental stage to the commercial application at the construction site. Table 7 shows the comparison of 3D printers by their performance in terms of spatial and technical parameters.

Gantry 3D printers are the most commonly used. The main limitation of the gantry is the small building volume, which suits the best for the mass production of small residential units, however, these printers are scalable (Paul et al. 2018). The printing area can be extended with the installation of the gantry on rails, which allows us to expand the length of the built object or to print the rows of units. The major benefits of robotic arm-based 3D printers are the ability to reproduce complex geometries and higher freedom of movement. The robots can be programmed for more complex actions, such as installation of the reinforced bars along with the printing process. The volume of printing for the robot is limited and can be used to produce the separate building elements (Puzatova et al. 2022). To achieve autonomous movement, a robotic arm can be installed on a crawler. The cable-driven 3DP is still in the experimental stage. The potential benefit of this technology is the use of lightweight construction, which can be easily transported into remote areas. The hybrid 3DP seems to be the future solution, which can benefit from the combination of the different technologies. Research in this field is ongoing, and currently there are developed gantry-based robots (CyBe GR), gantry-based cranes (DeltaWASP Crane), and truck-based 3DP(CONPrint3D).

3DP buildings initially have been constructed with the promotional purposes. Currently, 3DP settlements are constructed to provide fast and affordable housing to needy families. The price of the 3DP unit is significantly lower compared to the similar-size building. Most of these units are the single-floor single-family villas, which is the most efficient application of 3DP technology. 3DP is used as a tool for the automated walls construction, while the rest of the building structures is built using the traditional techniques and materials. 3DP is a solution for emergency housing, since it requires a few days for the construction (Naselli et al. 2022).

Table 5 Spatial and structural parameters of the case studies

Case study	Location	Function	Area, m^2	№ of floors	Design features	Material	Additional structures
Tabasco settlement	Mexico	Residential	46.5	1	Conventional	Lavacrete	Roof
Micro-Cabin	Netherlands	Residential	8	1	Organic	Bio-plastic	–
Westerlo house	Belgium	Residential	90	2	Conventional	Concrete	Slab, roof
Austin settlement	USA	Residential	46.5	1	Conventional	Lavacrete	Roof
Beckum house	Germany	Residential	160	2	Conventional	Concrete	Slab, roof
House in Virginia	USA	Residential	111.5	1	Conventional	Concrete	Porch, roof
Dublin residence	Ireland	Residential	430	1	Conventional	Concrete	Roof
House in Muscat	Oman	Residential	190	1	Conventional	Concrete	Roof
School in Malawi	Malawi	School	56	3	Conventional	Concrete	Façade finishing, roof
Luxury villa	China	Residential	1100	2	Conventional, prefabricated	Concrete	–
Eindhoven house	Netherlands	Residential	94	1	Organic, prefabricated	Concrete	Roof
Casa Covida	USA	Residential	20.7	1	Organic	Clay mixture	–
Dubai municipality	UAE	Administrative	640	2	Conventional	Concrete	Slab, roof
Dubai drone laboratory	UAE	Scientific	168	1	Organic, prefabricated	Concrete	Roof
Toilet units	Japan	Service	16	1	Organic	Concrete	Roof
House in the Netherlands	Netherlands	Commercial	100	1	Organic	Concrete	Roof
House in Saudi Arabia	Saudi Arabia	Residential	80	1	Conventional	Concrete	Roof
House in Russia	Russia	Residential	37.2	1	Conventional	Concrete	Façade finishing, roof
House in Italy	Italy	Residential	50	1	Organic	Mud mixture	Roof
TECLA house	Italy	Residential	60	1	Organic	Clay mixture	–
Gaia house	Italy	Residential	30	1	Organic	Mud mixture	Roof
Dior store	UAE	Store	80	1	Conventional	Mud mixture	Deck, roof
Hesse Sculpture	Germany	Residential	16	1	Organic	Mud mixture	Roof

It can be applied in areas that are hardly accessible, since the 3D printers can be transported by a truck and assembled on site. Due to automation, the number of specialists engaged in the building process is reduced. Despite this, the new construction technology is not reflected in building codes and standards, which complicates its application (Pan et al. 2021).

The size of the printed object remains the main limitation. The gantry of the 3DP can be scaled, but with increase of the dimensions, the difficulty of its transportation and assembly is growing. The other problem is the selection of the appropriate material (Guamán-Rivera et al. 2022) and its reinforcement (Yin et al. 2021). Multiple studies investigate the properties of the fiber-reinforced concrete mixture (Inozemtcev and Duong 2019). However, in the case of clay or mud mixture, research is limited. The technology has been fully applied during the last decade; therefore, the durability of the 3D printed buildings has been evaluated only by theoretical studies. Replacement of conventional construction with 3D printing is another objective of future construction. The use of domes and vaults in the building design, and use of the prefabricated elements can eliminate the necessity of the traditional roof and slab construction and reduce the complexity of the whole building process (Paul et al. 2018).

6 Conclusion

This paper is an overview of the most common systems of the 3D printers, which are currently used for construction. Comparison of the technical parameters allows choosing the 3DP with the better performance based on the size of the building, its design features, construction materials, and time and cost limitations. The second part of the research investigates the 3D printed buildings, which have been constructed and used as residential or commercial units. The summary gives an understanding of the current state of the art and limitations of technology.

Research in 3D printing for building construction is ongoing. The potential benefits of the automated on-site manufacturing, such as reduced transportation and labor cost, speed of construction, remote control, repeatability, accuracy, prefabrication, use of the building typological prototypes and possibility of building customization, are the main drivers for the further development of this technology. However,

Table 6 Specificity of the 3DP process

Case study	Construction time, hours	Building speed, m^2/hr	3D printer type	3D printer manufacturer
Tabasco settlement	24	1.9	Gantry	Vulcan II
Micro-Cabin	Not provided	–	Gantry	XL 3D printer
Westerlo house	504	0.2	Gantry	BOD2
Austin settlement	27	1.7	Gantry	Vulcan II
Beckum house	100	1.6	Gantry	BOD2
House in Virginia	12	9.3	Gantry	BOD2
Dublin residence	288	1.5	Gantry	BOD2
House in Muscat	120	1.6	Gantry	BOD2
School in Malawi	18	3.1	Gantry	BOD2
Luxury villa	24	45.8	Gantry	WinSun
Eindhoven house	120	0.8	Robotic Arm	Weber Beamix
Casa Covida	Not provided	–	Robotic Arm	SCARA
Dubai municipality	Not provided	–	Robotic Arm	Apis Cor 3D Printer
Dubai drone laboratory	504	0.3	Robotic Arm	CyBe RC 3Dp
Toilet units	60	0.3	Robotic Arm	CyBe RC 3Dp
House in the Netherlands	10	10.0	Robotic Arm	CyBe RC 3Dp
House in Saudi Arabia	168	0.5	Robotic Arm	CyBe RC 3Dp
House in Russia	24	1.6	Robotic Arm	Apis Cor 3D Printer
House in Italy	24	2.1	Cable-driven	BigDelta WASP 12MT
TECLA house	200	0.3	Hybrid	DeltaWASP Crane
Gaia house	100	0.3	Hybrid	DeltaWASP Crane
Dior store	120	0.7	Hybrid	DeltaWASP Crane
Hesse sculpture	50	0.3	Hybrid	DeltaWASP Crane

Table 7 Performance-based evaluation of the four 3DP technologies

Parameter	3D printer type			
	Gantry	robotic arm	Cable-driven	Hybrid
Printing area	Large	Medium	Small	Large
Printing volume	Large	Medium	Small	Small
Printing speed	High	Medium	Slow	Medium
Design complexity	Medium	High	Medium	Medium
Building completeness	Medium	High	High	Medium
Material	Concrete	Concrete	Locally sourced	Locally sourced
Technological complexity	Medium	High	Medium	Medium
Scalability	Medium	None	Medium	None
Teamworking	None	High	Medium	None
Transportability	Medium	High	Medium	High
Mobility	None	Medium	None	High
Prevalence	High	Medium	Low	Medium
Affordability	Medium	Medium	N/A	High

technology has multiple limitations. Research is needed in the fields of material science and structural engineering to improve the structural behavior of 3DP buildings. Another direction is the modification of the 3D printers in order to make them scalable, autonomously movable, faster and more precise. Furthermore, research shows the constant advances and increasing robotization in 3DP technology. The hybrid 3D printers using the robots installed on a gantry, crawler or truck allow the flexibility of movement, which increases the size and the complexity of the printed object. The robots can be programmed to perform the tasks of the concrete mixture pumping and the assembly of the reinforced elements at the same time. Drones can be used for the products delivery, which solves the logistics problem in hardly accessible areas (Mckinnon 2016). The emerging technology proposes to use the specialized drones for swarm-based multi-robot on-site manufacturing of all the building elements (Zhang et al. 2022).

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