SUSTAINABLE SMALL-SCALE HOUSING CONSTRUCTION USING 3D PRINTING: EVALUATION OF BUILDING PROTOTYPES

DOI: 10.26341/issn.2241-4002-2024-2a-1-T02030

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Abstract
3D printing is a rapidly developing technology which has been applied in various areas of industrial production. Large scale concrete 3D printing is a recent sustainable solution, which is affordable, can be applied directly on-site and allows to complete the building construction phase in a short time. By using the building prototypes 3D printing is suitable for small-scale affordable residential construction.

This study is based on the evaluation of six housing prototypes, which are suitable for construction using gantry and crane as the most common types of 3D printer. The height and area of the houses are limited by the working volume of the 3D printer. For each housing typology, the small-scale prototype was printed in order to evaluate its performance in terms of required number of materials, structural stability and construction time.

The results show that the 3D printing time depends on the complexity of the building shape. It allows the construction of straight walls to be completed two times faster in comparison with the traditional way of building. In the case of the domed ceiling, the difference reaches twenty times, since such a complex structure requires careful and pre-sized sitework. When applied to small-scale buildings 3D printing drastically reduces construction time, making it possible to build houses in case of emergencies and natural disasters.

Key words: *3D printing, housing prototype, affordable housing, sustainable construction*

Introduction

The applications of 3D printing techniques are numerous. The process of additive manufacturing, sometimes referred to as 3D printing, is accessible to both professionals and non-professionals due to the easiness of use (Dunn, 2012). Various materials are used by 3D printers as the basis of the technical procedures. Small 3D printers that employ plastic filament are reasonably priced and are often used for digital art and hobbies. The first 3D printer, created in 1981 by Kodama, uses photosensitive resin polymerized by UV radiation (BCN3D, 2020). In recent, as this technology gained popularity, several studies and improvements to 3D printing were carried out. Hull patented this technique in 1987 following the creation of the innovative and efficient stereolithography prototype SLA-1 (ASME, 2015). A number of 3D printing techniques, including Fused Deposition Modelling and Selective Laser Melting and Sintering, were developed during the following ten years (Sculpteo, 2020). 3D printing technology significantly impacts the way industrial production operations operate (Parupelli & Desai, 2019). The industrial framework changed in favor of producing customized items locally depending on consumer demand (Paoletti & Ceccon, 2018). Several industries, including manufacturing, architecture modeling, pharmaceutical and food sectors, as well as the fashion and apparel business, utilize 3D printers today. The most common 3D printers are based on the principles of VAT photopolymerization, binding jetting, materials extrusion, directed energy deposition, sheet lamination, and powder bed fusion. Each of these technologies is quite specialized and works in a different area of manufacturing (Shahrubudin, Lee, & Ramlan, 2019). There is increasing demand in businesses that specialize in building 3D printing, followed by the growing number of scientific studies and inventions in this field (IPOS, 2019).

Khoshnevis demonstrated the first 3D printer that could create a structure at 1:1 size in 2006 (Head, 2017). In 2014, DUS Architect investigated an innovative, faster and environmentally friendly method of construction by printing a small house out of plastic. In 2014 in China, prefabricated components, which were 3D printed in the manufacturing facility, were used by WinSun to build a house (Wu, Wang, & Wang, 2016). The same firm used a 150-meter-long 3D printer to construct 10 dwellings in one day (Feng & Yuhong, 2014). In 2016 MIT used a crane-based robotic to pour concrete over a circular route for building a dome (Chandler, 2017). In 2020, 50 single-family homes made up the first totally 3D printed town in Tabasco, Mexico (Schuldt, Jagoda, Hoisington, & Delorita, 2021).

Since 3D printing is presently being utilized to produce small structures, it has not realized its full potential in the building construction sector (El-Sayegh, Romdhane, & Manjikian, 2020). There are several advantages to using 3D printing on the building site, such as decrease of material waste and transportation costs (Shakir, 2019), error-free construction (Adedeji, Ojelabi, Omuh, & Tunji-Olayeni, 2019), accurate calculation of machine operating hours and amount of material needed (Inozemtcev & Duong, 2019), use of locally sourced resources instead of concrete (Abdalla, Fattah, Abdallah, & Tamimi, 2021). The fabrication of non-linear geometry and curved surfaces using a 3D printer is an effective method to overcome the constraints of conventional design (Sakin & Kiroglu, 2017). Architectural layouts are easily modifiable to meet the demands of various occupants and allow them to convey their own preferences (Mahdi, 2021). Due to the utilization of raw materials with minimal embodied energy and CO_2 emissions, 3D printing is considered to be a sustainable method of building (Hager, Golonka, & Putanowicz, 2016). According to several studies, a 3D printer can speed up building construction compared to using traditional techniques (Shakir, 2019), (Hager, Golonka, & Putanowicz, 2016), (Pandit & Kumari, 2021).

There are a number of restrictions on the use of 3D printers, such as limited building volume, and necessity to move the machine for the additional structural expansions. Installation of additional building elements and systems should be taken into account in the shell design stage because most 3D printers are only used to manufacture self-supporting exterior and interior load bearing walls (Romdhane & El-Sayegh, 2020). The last step of construction includes the addition of slabs and roofing, which are constructed with conventional methods and materials (García-Alvarado, Moroni-Orellana, & Banda-Pérez, 2021). The 3D printed surfaces are poorly finished, and the texture of the printing layers is evident (Ali, Issayev, Shehab, & Sharfraz, 2022). On-site 3D printing is highly dependent on the weather conditions, and the ground surface slope angle (Niemelä, Shi, Shirowzhan, Sepasgozar, & Liu, 2019). It demands to engage professional workers who have appropriate training in both digital manufacturing and masonry (Hossain, Zhumabekova, Paul, & Kim, 2020). Due to its rare use and long shipping distances, 3D printing equipment takes longer to arrive and costs more.

Methods

The study starts from the selection of the two types of 3D printers, which are currently used for construction of small buildings. Crane and gantry 3D printers are chosen since they allow us to compare two different approaches in technology. Two models, with are BOD2 and Delta Wasp Crane, are examined in order to define maximum height, and area of the building, printing speed, printing materials, complexity and completeness of structure.

In the second stage, six housing prototypes are designed according to the capacities of the 3D printers. The houses differ in size, being oriented to be dwelled by small, medium and large families, and in design approach, applying the conventional straight walls and the dome-like built structures.

Further, the small-scale prototypes were printed in order to test the structural stability and to estimate the printing time and the material volume. To find the performance of full-sized houses, the results were extrapolated and compared with the performance of the traditionally constructed buildings.

Prototype development

- Selection of 3D printers

Figure 1 shows BOD2 and Delta Wasp Crane 3D printers, which are selected for further evaluation. BOD2 is claimed to be the most sold 3D printer for construction. It has custom dimensions up to 14.6 m width, 50.52 m length and 8.1 m heigh which allows to print 2-floor buildings. It is among the fastest printers in the world because of its 100 cm/sec printing speed (COBOD, 2020). The dimensions vary between 3-30 cm in width and 1-4 cm in height, and the surfaces inside and outside are smoothed because of the use of flaps. Delta WASP Crane is supported by 3 structural elements and robotic arm pouring the material is placed in the center (ANIWAA, 2017). It is suitable for production of circularly shaped buildings and maximum radius is limited by the robotic arm length. The printing field can be expanded using the modular hexagonal pattern, where a series of Delta WASP Cranes can simultaneously. The largest model of Delta WASP is 12 m high and can print 2-3 floor structures with the speed of 40 cm/sec (WASP, 2015).

Figure 1 BOD2 and Delta Wasp Crane view and installation diagram

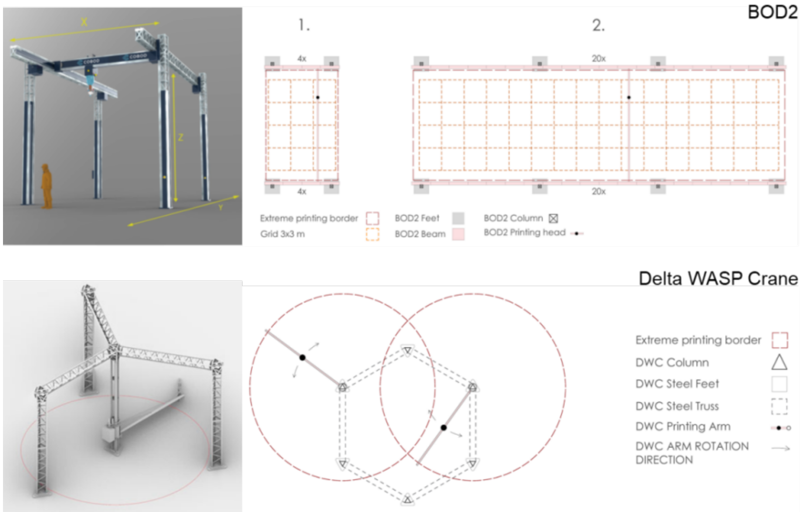


Table 1 describes optimal building design parameters, such as maximum building footprint, building area, number of floors, building material, construction time, design features, additional structures and elements, reinforcement, wall and roof type. BOD2 has larger dimensions and a larger maximum building footprint. Both 3D printers are preferred to be used for 1-floor construction. Due to the fact of the use of locally sourced materials, Delta WASP Crane is more ecological and cheaper in comparison with the concrete mixture used by the BOD2. BOD2 is faster and performs better in terms of construction time. BOD2 is used mainly for construction of conventional buildings, while Delta WASP Crane utilizes dome-like organic shapes. This means that BOD2 can only be used to build the walls, while the roof can be added later using traditional methods. Both printers can be used effectively for the construction, but due to the different technologies, the advantages and disadvantages should be examined after the development of prototypes.

Table 1 Design Parameters of BOD2 and Delta WASP Crane

Parameter	**BOD2**	**Delta WASP Crane**
Building Footprint, m	Rectangle 14.6x50.52	Circle B=6.3
Building Area, m^2	56-190	30-80
№ of Floors	1	1
Building Material	Concrete	Clay, adobe, mud, straw
Construction Time, hours	12-120	100-200
Design Features	Conventional	Organic
Additional Structure	Roof	-
Reinforcement	Required	Required
Wall Type	Straight	Curved

- Prototypes design

The prototype design starts with the definition of the spatial parameters of three main housing typologies. Based on the local design standard, the 1+1 house requires a minimum of 12 m2 of living space, or 14.52 m^2 of kitchen + dining + living room; 12 m2 of bedroom and 3.6-4.2 m^2 bathroom, the circulation space ranges from 4 to 5 m^2, and the total area should not be less than 50 m^2. In 2+1 module the living space should be 13 m^2 or 15.52 m^2 kitchen + dining + living room; 12 m^2 master bedroom, 8 m^2 second bedroom and 3.6-4.2 m^2 bathroom, circulation space is ranging from 6 to 7 m2 and the total area should not be less than 60 m^2. 3+1 house requires 14 m2 of living space, or 16.52 m^2 of kitchen + dining + living room; two main 12 m^2 bedrooms and 8 m^2 third bedroom, minimum of two 3.6-4.2 m^2 bathrooms, the circulation space ranges from 6 to 7 m^2, and the total area should not be less than 75 m^2.

The footprints of the buildings are calculated based on the technical specifications of the 3D printers (Figure 2). BOD2 is made of 2.5 long steel modules (COBOD, 2020). For the height (z) there are connected 4 modules with a total height of 10 m and for the width (x) - 6 modules with a total width of 15 m. The length (y) is infinite since an infinite number of elements can be mounted. The 3D printer frame is fixed using reinforced concrete footings under each column. Maximum building width is defined by the length of the structure excluding the footings and may start from 9.6 m (4 modules) up to 49.6 m (20 modules). Based on these limitations, a construction grid with 3x3 m unit was generated occupying 12x48 m space. After the grid was set, the building footprints were defined as 72 m^2 for 1+1 (A1), 81 m^2 for 2+1 (A2), and 108 m^2 for 3+1 house (A3). Delta WASP Crane is composed of a hexagonal base supported by triangular truss. Two robotic arms may work separately without colliding with each other during the 3D printing process. A grid is generated using circles with a radius of 3.2 m and is further transformed into a grid of 45º rotated squares. Multiple combinations of circles result in the following dimensions of the prototypes such as 131 m^2 for 1+1 (B1), 151 m^2 for 2+1 (B2), and 198 m^2 for 3+1 (B3) house. The space, which is adjusted next to the arched wall, is difficult to use, making the second typology larger in area.

Figure 2 BOD2 and Delta Wasp Crane construction grid

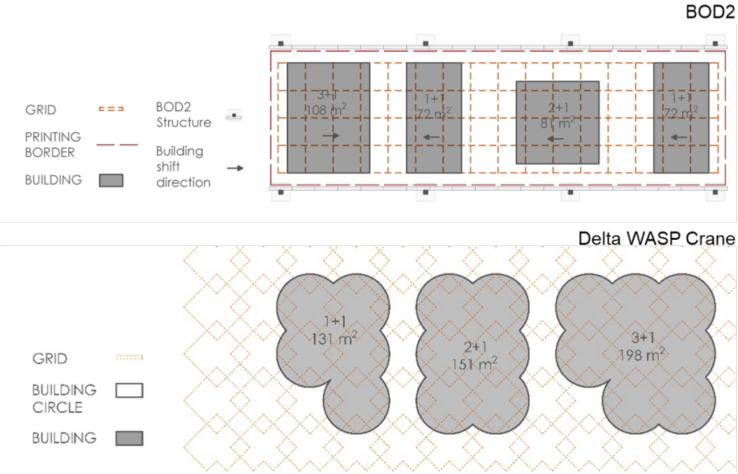
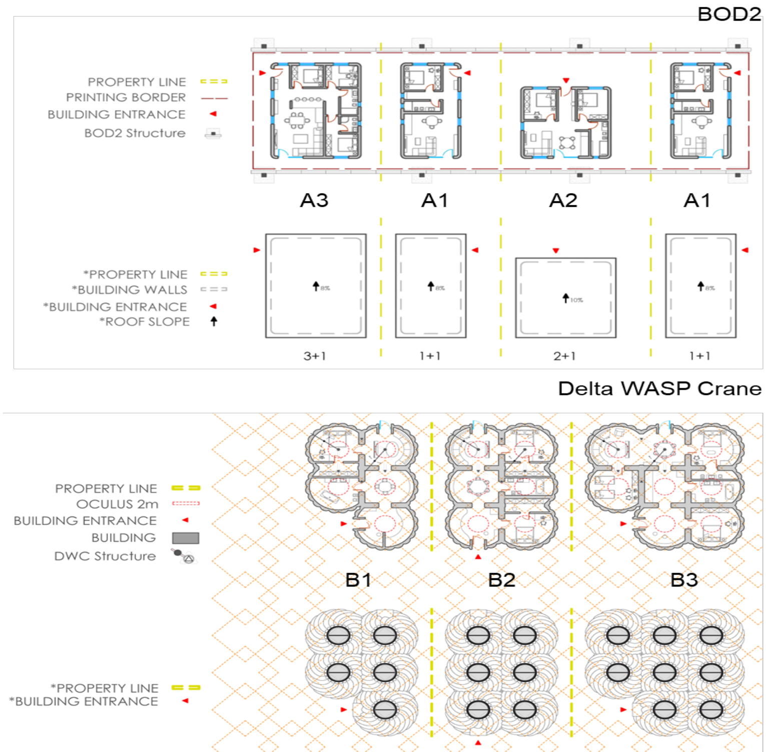


Figure 3 shows the ground floor plans and top views for each house. The A1 module is composed of a 28.6 m^2 common living space, 12 m^2 bedroom, 4.8 m^2 bathroom, and 17 m^2 corridor. A2 module has 21.4 m^2 living space, 2 bedrooms of 12.3 m^2 and 11.6 m^2, 7.5 m^2 bathroom and 14 m^2 is left for circulation. A3 house has 35 m^2 living space, 15.5 m^2 master bedroom with private bathroom, 2 other bedrooms of 8.6 and 8.8 m^2, 5.7 m^2 bathroom and 15.5 m^2 corridor. The roof has a slope of 8-10% and the corners are rounded in order to speed up the printing process. The second group of modules are designed to have curved walls and dome-like ceilings. Each dome has a base radius of 3.2 m. The B1 volume has a living room of 18.5 m^2, 25 m^2 bedroom, 21 m^2 kitchen and hall, 17.5 m^2 dining room, 16 m^2 bathroom and 5 m2 left for circulation. B2 is composed of an 18.5 m^2 living room, 25 and 24 m^2 bedrooms, 18.5 m^2 kitchen and hall, 17.5 m^2 dining room, 10 m^2 bathroom, and 6 m^2 circulation. B3 has a 21 m^2 living room and 17 m^2 dining room, 24.5 m^2 master bedroom (with private bathroom), 2 20 m^2 bedrooms, 15 m^2 kitchen, 12 m2 bathroom and circulation of 7 m^2.

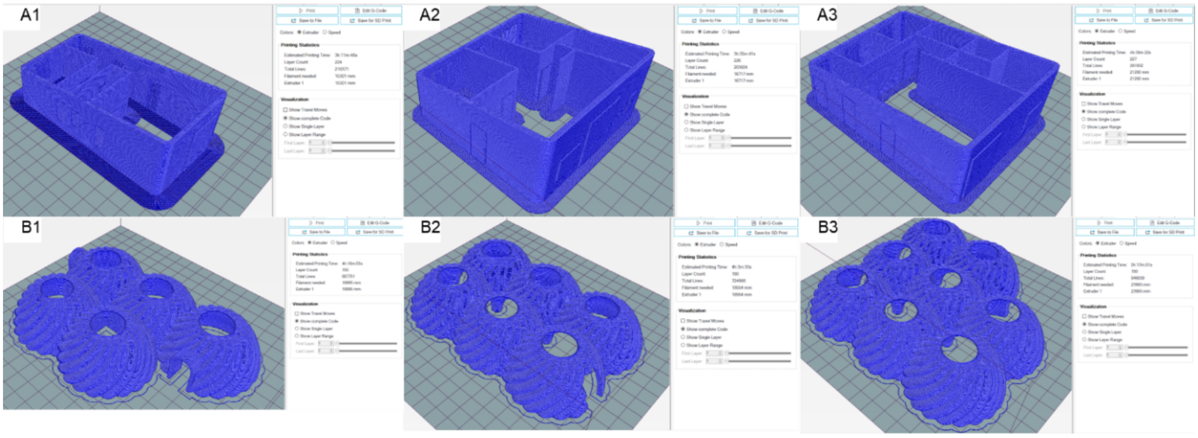
Figure 3 Ground floor plans and top views of six building prototypes



- 3D printing of small-scale prototypes

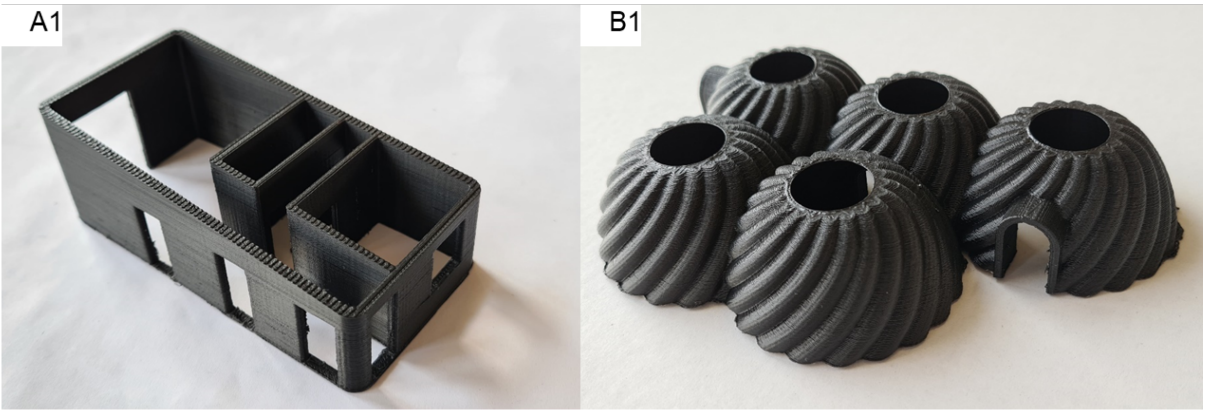
In the next step, the 3D model of each house prototype was imported into the Repetier Host slicing software (Figure 4). This software is used to prepare models to print in 3D, to calculate the printing time, material amount and the number of layers.

Figure 4 Preparation of prototypes for 3D printing



The 1/100 scale building models were printed in Digital Fabrication Lab of Epoka University (Figure 5). It took in total more than 4 hours to print, which is more than 3 hours and 12 minutes estimated by Repetier Host for the A1 prototype and 7 hours to print instead of 2 hours and 45 minutes for the B1 prototype.

Figure 5 1/100 scale 3D printed prototypes



Results

- Spatial parameters

Table 2 shows the area of each room and the total area for each house typology. The areas of Prototype A rooms are smaller, and the circulation space is larger than in Prototype B Most of the rooms in Prototype B have approximately the same areas, because of the design approach using overlapped circles. Some spaces in Prototype A, such as living room, kitchen and dining room, are merged, while in Prototype B they are all separated. The total area of Prototype A is smaller than Prototype B, because of the 3D printer limitations. The maximum height of Prototype A is defined by the height of BOD2 3D printer, which is 10 m, and in Prototype B the maximum height offered by Delta WASP Crane is limited up to 3 m. Prototype B has larger building volume and also requires larger property area.

Table 2 Spatial parameters of house prototypes

Parameter	Prototype					
	A1	B1	A2	B2	A3	B3
Living room, m^2	14	18.5	13	18.5	17.6	21
Master bedroom, m^2	12	25	12.3	25	12	21
Bedroom 1, m^2	-	-	11.6	24	8.8	20
Bedroom 2, m^2	-	-	-	-	8.6	20
Kitchen, m^2	8.6	21	4.7	18.5	12.2	15
Dining, m^2	6	17.5	3.7	17.5	5.9	17
Bathroom, m^2	4.8	16	7.5	10	5.7	12
Master bathroom, m^2	-	-	-	-	3.5	3.5
Circulation, m^2	17	5	14	6	15.5	7
Total area, m^2	72	131	81	151	108	198
Building height, m	4.5	3	4.5	3	4.5	3
Building volume, m^3	42.5	66.35	44.7	79.1	56.3	104.4
Property area, m^2	228	300	285	365	285	486

- Production time

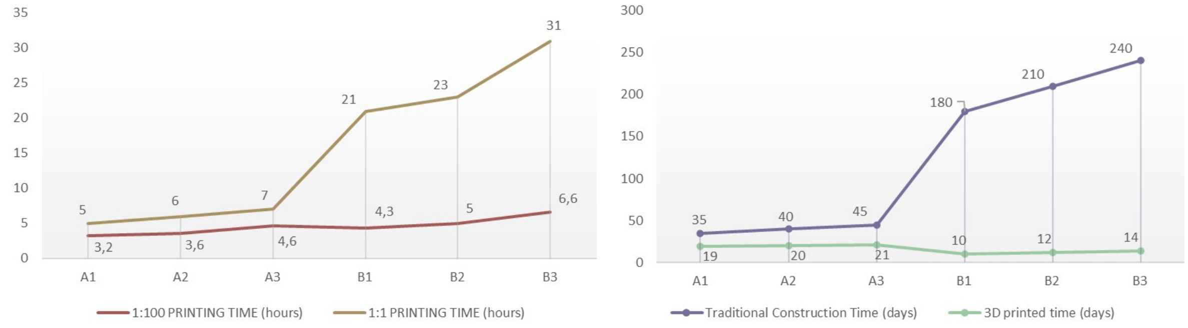
Table 3 shows the time required for the 3D printing of a small-scale and full-size building prototype and further estimates of time needed to complete the whole building using 3D printing and traditional techniques. Prototype A requires less time to print compared to Prototype B, due to the small building volume. Supports should be added to Prototype A in order to execute doors and windows. To calculate the 3D printing time needed for this process, there are taken average measures derived from the Repetier Host estimation and real performance. Calculation of the length of the 3D printed layers allows to find out the time, which is needed for the full-size construction since the printing speed of BOD2 and Delta WASP Crane is given in the specifications.

Table 3 3D printing and full building completion time

Parameter	Prototype					
	A1	B1	A2	B2	A3	B3
№ of layers	224	150	226	150	227	150
Supports	yes	no	yes	no	yes	no
1/100 3D printing time, hours	3.2	4.3	3.6	5	4.6	6.6
1/1 3D printing time, hours	3.5-5	19-21	3.7-6	4.7-7	21.5-23	28-31
Completion time using 3D printing, days	19	10	20	12	21	14
Completion time using standard methods, days	35	180	40	210	45	240

Calculation of the full construction is done through a common construction time estimate. It is assumed that the workers spend on the construction site 8 hours per day. All buildings have a slab foundation above, which takes around 5 days to be completed. Traditionally constructed buildings are built using reinforced concrete columns, exterior brick walls, interior gypsum board walls and a wooden roof. Thus, the columns require 5 days, the roof reinforced structure - 4 days, and the roof finishing - 10 days. 11 days are needed for finishing parts such as stucco, hydraulic installations, and electrical installations, furnishing. The number increases with the growth of the building area. It takes 35 days to complete A1, 40 days to complete A2, and 45 days to complete A3. Application of a 3D printer reduces the time approximately twice. Prototype B requires around 6 months to compete B1, 7 months for B2, and 8 months for B3 due to the complexity of shape, while the 3D printing of the same structure takes around 3 days. Figure 6 shows that even in the 3D printing time of Prototype B is bigger than A, in comparison with the conventional techniques it gives a great advantage in time.

Figure 6 3D printing and full building completion time



Conclusions

The main purpose of this study is to show that the application of 3D printing technology for construction is appropriate and efficient to build low-cost dwellings. BOD2 and Delta WASP Crane are chosen since they have an advantage in printing speed, printing volume, and total cost (Bici & Yunitsyna, 2023). BOD2 has the largest printable area which can be increased infinitely by adding more structural elements, while Delta WASP Crane has a small printable area which can be increased by adding more 3D printing cranes. BOD2 has the highest printing height up to 10 m, while Delta WASP Crane can print at a maximum height of 3 m, which limits the design height. BOD2 uses a mixture of concrete Delta WASP Crane utilizes locally sourced ecological materials, which makes the construction more sustainable and lowers the cost of the building. BOD2 is the fastest 3D printer for construction in the world (100 cm/s), and Delta WASP Crane has a lower speed (30 cm/s) which increases the time of printing.

Among the two approaches towards housing design, Prototype A is the most efficient in terms of area and height while Prototype B has an advantage in terms of structure, material, total construction time and the elimination of extra labor. The Delta WASP Crane seems to be a more appropriate 3D printer for the production of sustainable low-cost shelters. BOD2 can print the same model and has more opportunities for its further improvements in terms of raising the height and decreasing the footprint of the building. Therefore, further research can be based on the combination of prototypes and design of buildings that have a smaller footprint area and don't need any additional structures, such as roof trusses and finishings. In this case, after implementation of sustainable construction materials, BOD2 is the most appropriate 3D printer in terms of speed, cost, and spatial performance.

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