The Study of Additive Manufacturing Technologies with the Purpose of its Implementation in Construction Sector

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Abstract: Additive manufacturing technologies (AMT) has become one of the main trends in the development of innovative technologies in construction sector. The study examines the implementation of AMT using practical and illustrative example of its utilisation. In order to demonstrate and describe the sequence of steps 3D model of undersized building was created using fused deposition modeling. The methodology applied is model-driven. It was chosen in order to collect the experience, compare it with previous studied and use to the realistic manufacturing process. The aim of this paper was to identify possible limitations and challenging issues requiring further consideration and development. The main assumptions of this experiment are stated below with the purpose to explain the results obtained properly. In this study limitations of the previous studies are highlighted and possible solution methods are described referring to literature review and analysis. The main steps of AMT are shown step by step aimed to consistently study and reproduce the real process. The obtained information could broaden the current knowledge and help the researchers to apply the 3D printing (3DP) to access the full potential of it. Moreover, the paper also hypothesized the possible future directions for the future studies. Overall, the current key challenges to overcome in the nearest future are presented and discussed with a view to enable clean insights of AMT integration in construction sector.
Keywords: additive manufacturing, additive construction, construction technology, construction automation, digital construction, 3D printing, 3D model, civil engineering, emerging technology, fabrication, construction design, technology adoption.

Introduction

Over the last few years additive manufacturing technologies (AMT) appeared and finally took their place in the construction sector. The term “additive manufacturing” has come to be used to refer to layer-by-layer creation of an element based on a previously prepared digital model with almost any geometry [1 – 3]. The generally accepted use of AMT refers to a wide range of compatible materials [4 – 6]. Vlasova et al. reach the conclusion that the popularity of using such technologies in construction sector is already predetermined [5]. AMT are recognized as to be utilized in combination with the traditional ones [7].

A growing body of literature has examined the possibility of using AMT in the construction sector. Few researchers have addressed the question of modeling the structures behavior [2, 8]. Gardan et al. mention the process of numerical simulation, but without isolating it as a separate process [2]. The authors associate this process with the material data obtained. However, the necessity of 3D model standardization and verification is an important issue for future research [6].

The information presented in this study is aimed at the examining whether 3DP is compatible with complex structure production. One of the main issues what we know about main steps of additive manufacturing is a lack of numerical modelling and simulation.

The assessment was made based on the possibilities of performing construction work through automated additive processes. The following tasks were accomplished in accordance with the mentioned above purpose: to simulate and describe the project development process including its subsequent fabrication using 3DP.

This paper presents the 3D model design and its subsequent fabrication in order to practically demonstrate the sequence of steps and indicate the gap in knowledge. The undersized sample of a possible building model and its designing is the focus of this research. The printed model is the example of the Art Deco style (Fig. 1). The building prototype was created at the scale of 1:100. The reduction of the main building dimensions was carried out in order to systematically study and simulate the main steps of the creation, preparation and implementation of the project using 3D printing.

Fig. 1. – Building model facades

Main steps of 3D model design with the use of AMT

All AMT are practically the same. Their process is based on the identical sequence of steps. The undertaken study has confirmed the main steps of 3D model design and fabrication. The main steps depend on the applied technology and raw material. Generally speaking, there are 7 steps [9 – 11]:

1. 3D modelling using CAD-software and its verification;
2. export file to another file extension, such as .stl;
3. “slicing” or converting the 3D model file into G-code;
4. set up 3D printer and prepare the design;
5. 3D printing;
6. post processing;
7. shipping, adjusting, fixture (when required).

Research methodology

The research was carried out following the main steps of AMT described above. The software program used to design the 3D model was Autodesk AutoCAD. The equipment utilized was MakerBot® Replicator® Z18 3D printer. The utilized 3D printer works in accordance with the FDM-technology (fused deposition modeling).

The process of 3D model design and task preparing

In order to demonstrate the possible application of 3DP in construction sector the designed model was divided into structural elements. This assumption was related to a hypothetical comparison of printed elements with their potential use in real projects as prefabricated structures. The elements were divided by height Z. Within one height, the walls were divided along the directions of the walls (along X and Y). The wall parts are connected to each other using mortise and tenon joint. The mortise and tenon joint was used only for walls within the same height Z, while other elements were connected using overhanding and protruding parts.

Once the model had been designed from solid bodies, it was cut into separate parts using sectioning. The final building model consisted of 11 parts (Fig. 2).

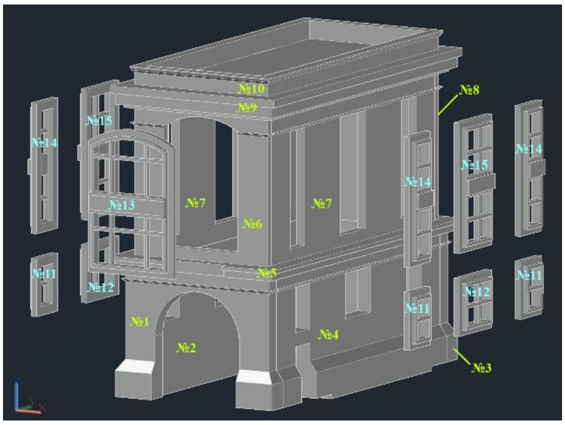

Fig. 2. – Model parts numeration

The model elements were created in such a way that there was no need for support structures during 3D printing. In order to achieve this an orientation change was made in the print preparation program. For example, element №3 was printed in a vertical position and element № 4 in a horizontal position (Fig. 3).

Fig. 3. – Different parts position during 3D printing for part №1 and part №4

The windows were created using support structures for overhanding and protruding parts (Fig. 4). The overhanging frame along the perimeter of the windows allows the elements to be installed without the use of additional adhesives.

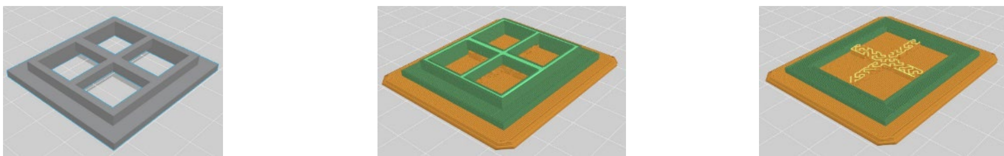

Fig. 4. – The overhangs presence of part №12

The printing time was calculated taking into account the flat base in order to increase the adhesion between the printed layers and to prevent warping due to their uneven cooling. General print information on 3D printing separate elements is presented in Table № 1.

Table № 1

Print information

Part	Number	Each size (X x Y x Z)	Print time	Plastic volume
South entrance to the first floor (№1)	1	120 x 15 x 90 mm	3:2 h	27.52 g
Western wall of the first floor (№2)	1	15 x 232 x 93 mm	6:52 h	103.05 g
North wall of the first floor (№3)	1	120 x 15 x 90 mm	3:21 h	44.92 g
Eastern entrance to the first floor (№4)	1	15 x 232 x 93 mm	6:47 h	99.73 g
Lower cornice (№5)	1	125 x 255 x 7.5 mm	4:30 h	50.52 g
South wall of the second floor (№6)	1	106 x 7 x 115 mm	2:56 h	22.22 g
Western (eastern) wall of the second floor (№7)	2	8 x 226 x 115 mm	5:33 h	91.38 g
North wall of the second floor (№8)	1	106 x 7 x 115 mm	2:52 h	34.68 g
Upper cornice (№9)	1	125 x 254 x 15 mm	11:11 h	160.42 g
Upper part of a wall and roof (№10)	1	106 x 234 x 17.5 mm	4:5 h	45.83 g
Small window of the first floor (№11)*	3	7 x 28 x 39 mm	30 h	4.55 g
Large window of the first floor (№12)*	2	7 x 43 x 39 mm	43 h	6.49 g
Stained glass window of the second floor (№13)*	1	10 x 65 x 98 mm	1:51 h	15.93 g
Narrow window of the second floor (№14)*	4	9 x 28 x 88 mm	1:15 h	11.27 g
Wide window of the second floor (№15)*	2	9 x 43 x 88 mm	2:41 h	23.17 g

Note: the marked parts (*) have overhangs, for this reason they are printed with the support structures that were removed after the printing was completed. The presented printing time of the marked parts was estimated taking into account the support structures (grids)

As soon as the 3D model was designed in the CAD program, it was checked. Then the model parts were exported in .stl file extension for following print preparation. The accepted characteristics of 3D printing process are given in Table № 2.

Table № 2

Print characteristics

Parameter	Value
First layer height	0.20 mm
Subsequent layer height	0.08 mm
Filling density	20%
Perimeter and filling line width	0.3 mm
Shell thickness	1 mm
Number of shell perimeters	3
Filling pattern	Octagon

After 3D model had been designed and checked, the task for 3D printer was prepared in G-code with .MAKERBOT file extension. At this point the printing path was generated.

The process of 3D printing

After the 3D printer was carefully prepared, the printing process itself could be started. The 3D printer uses REC PLA plastic with a filament diameter of 1.75 mm (Fig. 5).

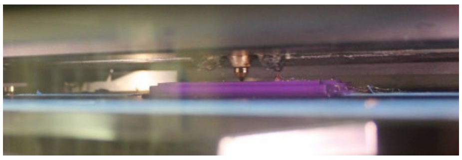

Fig. 5. – The extrusion process of part №13 with the use of 3D printer

Post-processing procedure and assembly after 3D printing

After the printing was completed, all the parts were assembled together. The support structures were necessary to be removed for some parts (№11-15) (Fig. 6).

Fig. 6. – The removal of the support structures

All the parts of 3D model were assembled together (Fig. 7).

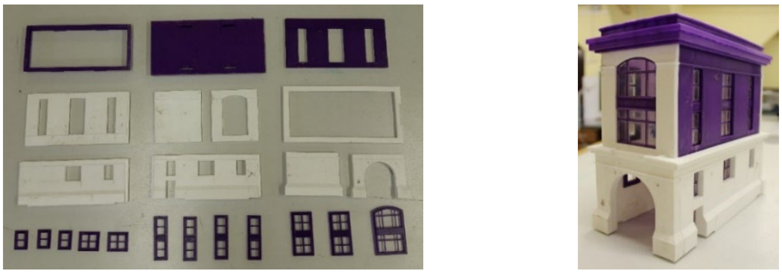

Fig. 7. – The assembly of the printed building model elements with the glass installation

For greater clarity, the GCC LaserPro Mercury III ME-25 laser engraving machine was used to cut windows from organic glass and doors from plywood (Fig. 8).

Fig. 8. – The processes of glass manufacturing and installation in the printed windows

All surfaces were sanded, primed and then coated with paint and varnish (Fig. 9).

Fig. 9. – 3D model post-processing and finishing

Challenges of 3D model design and manufacturing

The occurred challenges of 3D model design and manufacturing relate to the FDM technology and PLA plastic used by 3D printer. One of the main difficulties is due to the fact that the creation of overhanging parts is impossible without the support structures utilization. For this reason, different parts orientation was specified during the task preparation. In other words, the model design depended directly on the ability to print in one orientation or another. Windows, as mentioned above, could not be printed without support structures if there are overhanding and protruding parts.

Considerable attention was paid to the connection of the parts between themselves. As already mentioned above, the parts of the walls were connected to each other using mortise and tenon joint (Fig. 10).

Fig. 10. – Mortise and tenon joint of the 3D printed parts

Based on the possibility of individual structural elements 3D printing, an assumption is made about the possible application of AM technologies in the prefabricated structures manufacturing. This assumption is consistent with the main steps of production mentioned above. Once 3D printing is completed, the finished elements can be delivered and assembled at the construction site.

The building model obtained is a prototype of a 3D model with a good detailed accuracy (Fig. 11).

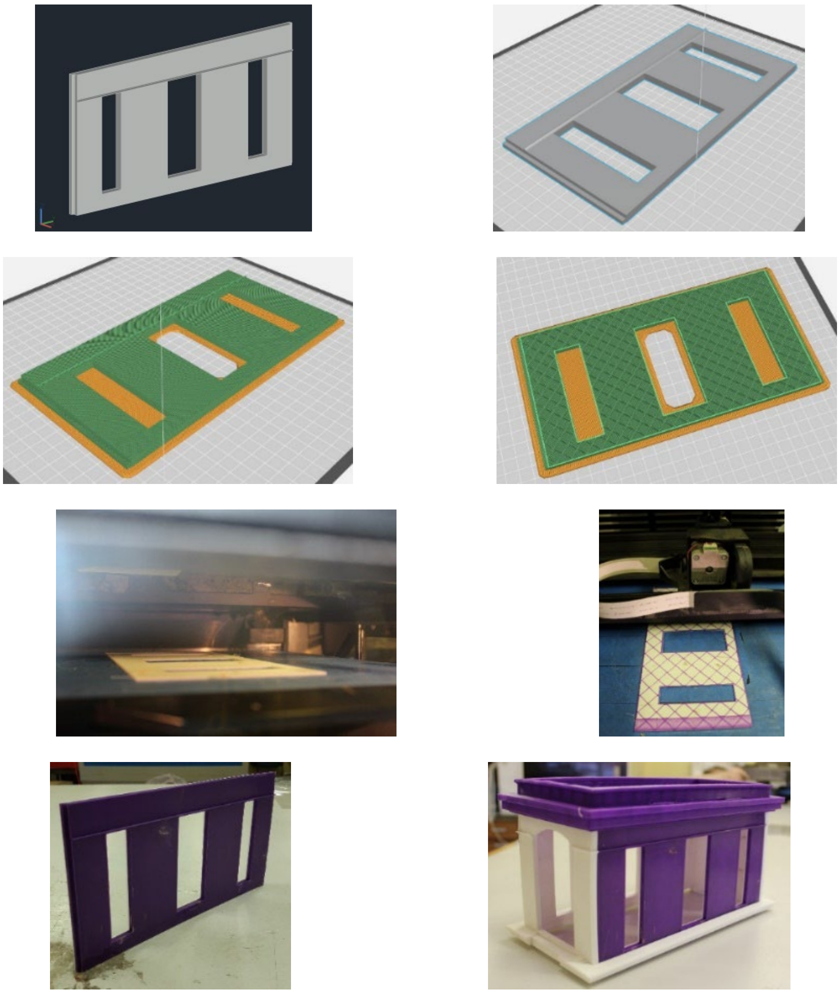

Fig. 11. – The process of creating element №7 using AMT

The difficulties occurred during 3D printing can be considered as reference material for subsequent research.

Analysis of the 3D printed model

The 3D model of the building obtained during the experiment indicates the achievement of the set goals. This paper provides the study and description of the main steps, as well as the main difficulties associated with this. In this case, the structural solutions for parts connection serve as guidelines and designed to meet the requirements in accordance with their implementation options.

By analysing the model obtained in comparison with the developed 3D model in the CAD program, we can talk about its reliability (Fig. 12). As a result, the conducted study can serve as the possible introduction of 3DP into the construction sector.

Fig. 12. – Comparison of the 3D model developed in the CAD program model with the 3D printed one

Conclusion

As expected, our study showed the sequence of steps. The main steps were demonstrated practically. The process of 3D model design and verification fits well with the mentioned above studies but indicates the gap in knowledge of numerical modelling. The study of the AMT processes confirmed the close relationship between separate stages of production, as well as the existing need for their comprehensive control.

In our view the result emphasizes the accomplishment of the stated aims. The process of preparing and manufacturing 3D model using 3DP was presented. The difficulties faced during the creation of 3D model and possible ways to overcome them were described with the reference to the material used.

It is essential to conduct a more detailed study of this process in order to enhance the understanding of the real structural behaviour. Further studies, which take numerical modelling and simulation into account, will need to be undertaken. In this case the finite element method is suitable for it. This can be confirmed by an easily exportable file in both issues task preparing files and finite element method files [8, 12]. A further challenge is the interpretation of the results obtained after analysis using finite element method.

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