The additive manufacturing in road construction as factor of its sustainability in conditions of climate change and hydrological catastrophe

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Abstract. The necessity for technology incorporation has appeared in the construction sector a long time ago. A challenging area in the field of construction touches upon design, build, operation, maintenance, reconstruction and include all the steps of a process. This paper calls into the question of additive manufacturing (AM) application in the construction sector, especially road construction, describing the AM implementation. The model-driven methodology is critical to the success of manufacture. Key challenges that face construction 3D-printing are presented and discussed. The aim of this article was to show exhaustively realistic prospect of AM in road construction as factor of its sustainability, in particular in conditions of climate change and hydrological catastrophe. Furthermore, the experimental simulation was conducted to enable clean insights into the AM process. These insights could be fundamental to further experimental investigations with an eye to estimate the use of traditional already well-established construction materials. The presented opportunities elucidate the demand for on- and off-site CAD integration. The conducted experiment demonstrated all steps of AM.

1. Introduction
In the modern rapidly developing world mechanization and digitalization are universally among us. Practically every construction sector has already made the use of automation. Nowadays application of this technology has been well known for some time in construction sector as well. As opposed to almost every industry sector that successfully had involved automation [1, 2]. The fully or partly automated layer manufacturing is called additive manufacturing (AM) or 3D-printing [3]. AM could be less effective as in comparison with other sectors as a result of large size [4]. It is well known that construction is rather labor intensive, cost and highly accident industry [5, 6, 7]. Much work on the potential of AM has been carried out, however there are still some critical issues driven by few real examples. The first studies of AM implementation considered it to be a good solution in effectively management of raw materials usage [4]. Furthermore it could reduce the cost of raw materials [8]. The construction sector is expected to be improved on several main directions. The idea of providing new areas is also of particular interest [8]. The key factor for further detailed understanding and sustainable development is the understanding of the mechanical behavior of 3D-printed samples [6]. Another main
focus could be attended to the design architectural form freedom that allows to design non-linear form without any additional formworks. The absence of formwork necessity is one of the main advantages of AM technology [1, 5, 7, 8, 9, 10, 11, 12].

This paper describes the technology of AM process drawing on the example of road construction, which is bridge with culverts (collecting pipes). Such structures are the first that can be destroyed in conditions of hydrological catastrophe, in this case, the increase of their sustainability is vital problem nowadays [13].

Most studies of AM in construction have only focused on building construction. The AM application in engineering construction and in particular in road construction has corresponding efficient approach. In the literature there are several examples of AM application in road construction. One of the bridges was consisted of metal and created by the printer called MX3D that has 6 axis robotic welding arms. It was the first additively manufactured metal bridge. The printer works on the basis of selective laser sintering (SLS) of powdered metal technology. The steel components were printed by the multinational engineering firm Arup and researchers from Imperial College London. The bridge length is 8 (10) m, width 2.5 (4) m, and located in Amsterdam, Netherlands. It was manufactured with the use of fitted robots with a welding attachment. The printing process took place off-site, as on-site construction was revealed to be too dangerous. The developed 3D-model was also used in the numerical solutions and load-testing [2, 8].

Another example is pedestrian bridge in urban park near Madrid, Spain that was finished in 2016. It was created by the Institute of Advanced Architecture of Catalonia and Enrico Dini. It is called Castilla-La Mancha 3D bridge. As stated by the authors it was the first ever 3D-printed bridge. Its span is 12 m and width 1.75 m. The bridge consists of 8 parts and was printed within the 2 months through the fused concrete powder and polypropylene reinforcement. Another interesting point is that no raw materials were used, as the fused material consisted of recycled components. The opportunity of using recycled materials proves the manufacturing technology to be ecologically friendly [2, 8].

One more bicycle bridge that was made from concrete is in Gemert, Netherlands. It was underlined that it was the first 3D-printed prestressed concrete bridge. It was manufactured by BAM Infrastructure and TU Eindhoven. The bridge length is 8 m and width 3.5 m. During the creating process 1 cm of concrete were extruded through the nozzle. The extruded concrete could maintain its form without any additional formworks after deposition. The manufacturing process was conducted partly. Then on-site all the parts were assembled together and the construction was tested [2, 14].

These examples are surprising from the view that used material was a metal that considered to be still less usable in construction. But not only structures itself could be created with the use of AM but also bridge pier sheaths that were printed and changed the old damaged ones due to scour [15]. There are some examples that show the linkage between 3D-model for AM application development and functional component topology optimisation. It proves that the obtained due to AM process 3D-model will be required for the further calculations and mechanical design of structures [16].

AM has also applications in the field of road construction. The AM application has come to be used to design, build and repair (reconstruction). In the eventuality that surrounding environment would be unfitting for the 3D-printer the structures could be printed off-site and then assemble together on-site. In Shanghai were adjusted 3D-printed sound barriers around the city highway. Their length along the S58 Shanghai-Changzhou Expresswayis 70 m. It is stated that with the use of them the highway noise would be successfully reduced. These constructions are much more effective than the traditional ones. The project was carried out by the Winsun company that is well-known for its AM application in construction sector. In December 2019 another road project was conducted in the Yunnan Province of China. The slope protection of the highway was created and tested [17, 18, 19, 20].

The paper is focused on AM application in the context of repair design, build, operation, maintenance and reconstruction with the use of CAD (computer aided design) and BIM (building information model) technologies. Digital manufacturing makes construction process more effective and can be considered as factor of improving its sustainability. Construction sector is recognized as being elusive, costly due to the use of service equipment and subjected to injury accidents. It is
generally accepted that the AM application is able to resolve these conflicts [5]. This raises many questions about AM implementation but due to its technology adoption the prospect is advantageous. This paper re-examines and calls into the question of combined application of AM and BIM in construction. It has become a reality, for this reason BIM and CAD would be indispensable component. There are still numerous unexplored problems in AM technology [12, 21].

2. Materials and methods
This paper is focused on the process of manufacturing of road construction elements. The conducted experiment was used to obtain an undersized sample modelled on a probable bridge. A small sample size was chosen due to the process performance capabilities to show all steps of realistic project preparation. The model consisted of bridge in neotudor style and 3 collecting pipes, for that the special curved arch was also arranged.

Commercially available software was used. The software application used to model design and development was the Autodesk AutoCAD 2018 with the free software access for students and educators that was downloaded from https://www.autodesk.com/education/edu-software/overview. For 3D-modelling was used «3D Modeling» workspace. The model was created with millimeter measurement scale in order to be acceptable to 3D-printer measures. The device used was 3D-printer Picaso Designer X PRO. Technical specification are presented in table 1.

| Specification         | Value                              |
|-----------------------|------------------------------------|
| Print technology      | Fused Filament Fabrication (FFF)   |
| Extruder number       | 1                                  |
| Nozzle number         | 2                                  |
| Printing zone         | 200 x 200 x 210 mm                 |
| Printing speed        | Up to 100 cm³/h                    |
| Minimum layer thickness | 10 microns (0.01 mm)            |
| Filament diameter     | 1.75 ± 0.1 mm                      |
| Nozzle diameter       | 0.3 mm (0.2 - 0.8 mm)              |
| Build platform        | Aluminum, glass                    |
| Guide ways            | Guide rail - XY Rail, steel; Z Cylindrical, steel |

The printer is based on FFF-technology (fused filament fabrication) that comprises thermoplastic polymer filament melting and layer-by-layer model building up. Figure 1 shows the schematic illustration of the operating principles of 3D-printer.

The software application used to analyze the model data was PICASO 3D Polygon X software version 1.5.6 with free access. It was downloaded from https://picaso-3d.com/ru/techsupport/soft/designer-x-pro/. This programm was also utilized to create a task for 3D-printer in G-code with .plgx file extension. It was decided to joint all printed parts by dichlorethane plastic glue. The used material was 3D Printer Filament PLA by REC with diameter 1.75 mm the colour white (RAL 9003).
Figure 1. Schematic illustration of the operating principles of 3D-printer

Table 2. Print characteristics

| Part                  | Number | Each size (X x Y x Z)    | Print time | Plastic volume |
|-----------------------|--------|--------------------------|------------|----------------|
| Pipe type 1 (№1)     | 2      | 22.5 x 60 x 15 mm        | 4:16 h     | 18.8493 cm³    |
| Pipe type 2 (№2)     | 1      | 30 x 60 x 22.5 mm        |            |                |
| Bridge type 1 (№3)   | 2      | 23 x 74 x 22.5 mm        | 5:12 h     | 23.9946 cm³    |
| Bridge type 2 (№4)   | 2      | 67 x 65 x 37.5 mm        | 12:02 h    | 51.2646 cm³    |

In the first step by creating different solid shapes and their mutual editing were received the designed bridge and collecting pipes model. The 3D-model was prepared as described above in CAD-program (figure 3a). After the full model has been done, we can then slice it in proper for 3D-printer parts. This operation was done in an attempt to reduce model size and accelerate processing and printing. The final model contained 7 parts at all: 3 collecting pipe parts and 4 composing bridge parts (figure 2). Print characteristics are presented in table 2. The scaling was pretended to be symmetrically.

Figure 2. Model parts numeration

To determine whether any faults, holes or flipped normals the model should be carefully checked for it before the next step. This problem can be posed in terms of affordable sample size, edge thickness, engraved or embossed details. It was decided that the best method to overcome this problem were external visual examination and after program slicing verification. The print task settings are reported in table 3.
Table 3. Print characteristics

| Parameter                        | Value |
|----------------------------------|-------|
| First layer height               | 0.20 mm |
| Subsequent layer height          | 0.08 mm |
| Filling density                  | 25%   |
| Perimeter and filling line width | 0.3 mm |
| Shell thickness                  | 1 mm  |
| Number of shell perimeters      | 3     |
| Filling pattern                  | Octagon |

As soon as this step was successfully carried out the model was adjusted to printing path. At this point the 3D-printer was adjusted to start printing. The platform and nozzle heat temperature was choosen in accordance with material. Before printing the special adhesive glue PICASO 3D was applied to increase adhesion. It was necessary for the model not to come off the platform. The used material was selected and inserted (figure 3b). And finally the special file consisted of G-code with .plgx file extension went to 3D-printer. The G-code had fully detailed printing path dedicated to 3D-printer. And now we are ready for the next step, printing. As the printer is based on the FFF-technology the sample was created by material extrusion of melted material. The next layer cross-section was deposited before the previous had fully solidified. The procedure continued following the steps outlined above till the print head was gone through every printing path of each layer (figure 3c,d).

![Figure 3](image)

**Figure 3.** AM process of side part. (a) - 3D-model; (b) - first layer defining; (c) - extrusion process; (d) - higher layer printing; (e) - finished sample part.

Considerable attention must be paid when the printing process has just started. During the first layer printing the unsuitable value of heat temperature could be discovered. Therefore great care should be paid to the arranging process. After the printing was complete the printhead moved to the parking position and the build platform went lower down (figure 3e). We waited for 15-20 minutes for the glass to cool down after printing and then removed the sample from the printer.

3. Results and discussion

The AM preparing and manufacturing process is presented. Compatible construction materials are still poorly known to be used in AM but the material technology development is necessary to be exercised along with other aspects such as technological processes. Our method has many attractive and practical applications concerned with AM application. During the preparation were solved many important issues of the 3D-model. We believe these problems have subsequent effect. This means that many other researches could face them.

The presented pictures showed the process how is the 3D-model step by step created (figure 3). As already mentioned above, while the model for its integrity were checking, were used both visual examination from all sides and verification in the program slicing. During the visual examination, it was necessary to take into account the printer characteristics and the principles of material extrusion.
In the program slicing and preparation for printing the main operations were controlled during the further sample construction. During the printing process, as already mentioned above, the first layer is the most important and critical, since an incorrectly selected value of build platform (bed) heat temperature can lead to poor adhesion between the ejected material and the platform itself, which will inevitably lead to the separation of the sample printed part from the build platform. For this reason the use of special adhesive glue PICASO 3D was critical.

After the model was successfully printed, it was carefully visually examined. The printed edges and surfaces are assessed as satisfactory. The subsequent solution process of the sample was carried out in accordance with the model features obtained by creating with the use of this printer. Firstly, the edges were smoothed out and sanded. Then all parts of the model were glued together with dichlorethane plastic glue (figure 4). The setting time of the model parts was taken as 30 hours for the complete bonding of the surfaces. The assembled final model was a prototype of its 3D-model with great detailed accuracy. This indicates a successful experiment and the aims and objectives fulfillment that were set at the beginning. All the difficulties that appeared during the experiment were described in this article and can be considered as a reference material for subsequent AM experiments conduction. In other words the resulting sample can be expressed as considerable progress that has been made towards the aims.

Figure 4. The printed model assembly. (a) - before; (b) - after.

As stated in the Introduction, the research was conducted to reveal and show AM process. Having a model experiment enabled us to believe in AM opportunity to perform large-scale building and construction structures, as the experiment was conducted as a scaled-down real production process. The traditional approach to create samples including molding is much more labor-intensive even on the experiment examples within the laboratory.

Our steps proceed are in the same way as [20] with the exception of the used material and attached printing technology. The data preparation, design and exploring algorithms are described for purposes of PLA plastic printing.

4. Conclusion
A striking feature of AM technology is the opportunity to extend sustainable productive development in conditions of climate change and hydrological catastrophe. As AM has become an important issue in Industrial Revolution 4.0 the technology implementation is one of the key questions. Within the next few years AM is likely to become an important component in major scientific research. Possibly by creating a more realistic model dedicated to specific surrounding environment the experimental process could also contain calculations and mechanical analysis of behavior. The fracture mechanics is still unclear and open area for further work.

The introduction chapter touches upon some the most interesting and outstanding examples of AM implementation. This section described the limitations during past knowledge and provided an initial understanding of some processes. It was also highlighted that various alternative ways should be
explored to overcome these problems and fully exploit the prospects. The second chapter described the conducted experiments and outlined the existing difficulties and potential ways to overcome them. The third chapter discussed the obtained results and the ways of interpretation. The existence of imperfection and was also mentioned in order to continue to deal with this matter. These experiments highlighted that mutuality interdependence between every manufacturing step is one of the major issues during the 3D-printing process.

The analysis did not reveal any significant data of construction materials as it should be investigated further. We are of the opinion that the validity of our model and experiment could help in AM implementation in the construction sector. It is still an emerging technology that needs standard documentation. These topics are reserved for future work to reach the targets mentioned above. And only in that case AM could access the full potential in the construction sector. Another key parameter to be in a greater detail studied is the topology optimization that plays an essential role not only in model design but also in efficient geometry and mechanical behavior of the hardened structure.

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