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3D printing of buildings and building components as the future of sustainable construction?

Izabela Hager*, Anna Golonka, Roman Putanowicz

Cracow University of Technology, Warszawska Str. 24, 31-155 Cracow, Poland

Abstract

The paper presents the state-of-the-art concerning the current achievements in the field of 3D printing of buildings and building components. The 3D printing technologies, comparing to traditional techniques of constructing the buildings, could be considered as environmental friendly derivative giving almost unlimited possibilities for geometric complexity realizations. Two kinds of technologies were described in this paper with pointing to Contour Crafting as a promising technique that may be able to revolutionize construction industry in near future. Numerous advantages of this technology, such as reduction of the costs and time, minimizing the pollution of environment and decrease of injuries and fatalities on construction sites could be cited. Despite many advantages and hopes, some concerns are summarized in the conclusions, as the technology still has many limitations. A brief description of few examples of pioneering usage of 3D printing in construction industry are presented (Canal House in Amsterdam, WinSun company and printing application for building carried out by Skanska company). Creating a model that will be appropriate for 3D printers is possible in many different modelling programs. One of the most popular formats for sharing such models is STL format. In the paper sample models crated in Autodesk Inventor are shown, but also other tools suitable for preparing models for 3D printing are briefly discussed.

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Keywords: 3D printing; concrete; contour crafting; building materials; sustainable construction

* Corresponding author. Tel.: +48-12-628-2371.
E-mail address: ihager@pk.edu.pl

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1. Introduction

The first 3D printer was invented in 1984 and over the last decades, 3D printing has become one of the fastest growing technologies. At the beginning it was very complicated and what is more, expensive technology. Over the years, 3D printing started to be present in everyday life and printers became commonly used in all kinds of industry fields. A lot of achievements have been made in medicine, automotive or aerospace industry. Thanks to the open source systems, prototyping of new product, and innovative applications of 3D printing in various fields are available for everyone.

Improvement of the printing material and 3D technology became to be the goal for many companies all over the world from all industry sectors. In 2014, real revolution in construction industry has started, as the first house was printed starting a new chapter in building technology.

The questions asked in this document are: is 3D printing technology effective enough to go out of laboratory settings and be embraced by building industry? To which extent 3D printing can replace traditional construction technologies? What are the application areas where this technology is to be applied first?

2. 3D printing technology and materials

The idea of 3D printing was born already in 1983, when Charles W. Hull came up with an idea of hardening the tabletop coatings with the UV light [1]. This simple thought has lead him to invention of stereolithography, first technology of 3D printing. Stereolitography was the first technology of rapid prototyping which means fast, precise and repeatable production of elements usually with computer support. First step in creating the technology was invention of additions to the synthetic resins that after lightening of the resins, were causing start of the polymerisation process. Stereolitography is a technology that can build objects with a high precision and extremely complicated geometry and that's the reason why it is used in many fields like for example: medicine, automotive and plane industry, and even art and design. Similar technique for 3D printing is selective laser sintering (SLS) in which laser is used to melt a particles of powder together to create an object. Materials used in SLS technology usually have high strength and flexibility. The most popular ones are nylon or polystyrene. Fused deposition modeling FDM is a technology that was invented in 1988 by S. Scott Crump [2]. Ductile materials which are hardening itself during cooling process, are extruded through double headed nozzle. Both, modelling and supportive materials are being deposited according to the cross-section layers, generated from digital model supporting the printer. The nozzle contains resistive heaters that keep the filament in appropriate melting point, which allows it to flow easily through the nozzle, in case to form the layers. Like in the other technologies, after creating one layer, a platform is being lowered and next layer is created. This process is repeated until the whole object is completed. Materials usually used in FDM technology are called filaments and are used in printers as a rolls of thermoplastic materials like ABS (*Acrylonitrile Butadiene Styrene)* or PLA (*Polylactic Acid*) – which is a completely different kind of thermoplastic. It's being made from corn starch or sugar cane and is biodegradable, so it is considered as greener and more sustainable than ABS. Over the past two decades, fused deposition modelling has become the most popular and widely used 3D printing method in the world. Wide range of materials were developed during the last decades presenting various properties and allowing to increase the range of applications and giving the prints the aspect of wood (*PLA with wood fibers*), metal (*PLA with bronze*), sandstone (*PLA with milled chalk*) [3].

3. Examples of 3D printing application in building industry

3.1. Canal House in Amsterdam

In 2014 Dutch designing company Dus Architects decided to build a house by printing its parts by a giant printer. In Europe, this is the first project that will be realized entirely by 3D printing technology. Project called 3D print Canal House takes place in Amsterdam and it is going to take at least three years. Architects from Dus Architects want to prove, that by printing components of the house directly on the site, they will be able to completely eliminate building waste and minimize costs of the transport. Mobility of the printer, is a considered as the main advantage as it may be transported all over the world, thanks to what, a cost of transport of the material and its storage on a building site will probably disappear. The time of the project was estimated, to allow them studying the technologies of the printing and developing the appropriate material. Building site is open to the public and it will remain open even after the project is finished, as the main aim of the operation is to discover and share potential usage of 3D printing in construction industry [4].

Components of the house are printed by a giant 3D printer called KamerMaker. Printing technique is very similar to most of the printers. Process starts on a computer, where in a respective 3D program models are being created and converted to the desired format. Thermoplastic material (what in this particular case is biodegradable plastic), is heated by the printer until it reaches appropriate liquid state, so it can be lay down by a printer's nozzle. After one layer is created, another layer is built on the previous one. In this stage of the process the most challenging thing to develop is a material that after fabrication by the printer will be at the same time flexible enough to create fitting layers, adhesive so the subsequent layer will join with the previous one and stiff enough so that the component will preserve its shape.

3.2. WinSun Company buildings

WinSun Decoration Design Engineering Co is a Chinese enterprise, working on material similar to concrete that will be suitable to use in 3D printing technology. In 2014 they have accomplished to build houses printed in 3D technology. This technology is based on building components printed as prefabricated elements and assembled on a site. Components are being printed by printer, 6 meters high, 10 meters wide and 40 meters long. The printer extrudes the material (mortar) through a nozzle layer-by-layer. Walls have diagonally reinforced pattern, with hollow structure that will be acting as insulation layer. Components are being printed in a factory and after printing, they are being transported to the building site and assembled together to create whole construction. Windows and doors were fitted in building walls (Fig. 1 b). After roof was installed, finishing works were done and buildings were completed. The estimated cost of each building is 4.800 dollars.

Year after Chinese developer has printed also five-storey building (Fig. 1b) using the same technique as for previous houses this building remains the tallest construction printed in 3D in the world [5].

a) b)

Fig. 1. (a) First house printed by a WinSun company in 2014; (b) Five-storey building printed in 3D [5].

3.3. In-situ Contour crafting

The most promising 3D printing technology used in building industry is called Contour Crafting (CC) technology. In this technology material is poured progressively layer by layer, however whole process is taking place on site. This technique gives a great opportunity of automation of the construction process, by using 3D printer that will be able to print a whole house directly on-site. The major advantages presented by Khoshnevis [6] is that the process that will be performed mostly by the machine, will be safer and that with use of appropriate material and with good parameters of the printer it will reduce its costs and time. 3D printing will also allow to create large components with unlimited architectural flexibility and highest precision. The idea of the inventor is to create a printer, that will have one or few nozzles that are moving on two parallel lanes installed at the construction site, separated from themselves a few meters wider than the width of the building. The next part of the process is the same as in previous technologies, material is extruded through the nozzle and laid down in a shape of empty blocks, with crosswise pattern inside to ensure desired stiffness and strength.

Existing example of Contur Crafting technology realization is from Andy Rudenko's garden, where he managed to build a castle (Fig. 2a and b), using technology and software from RepRap 3D printing open source project. Material used in a printer was a mix of cement and sand. Whole building was printed on a single run, except of towers, that were printed separately and assembled to the building [7].

a) b)

Fig. 2. (a) First structure printed in-situ; (b) printing progress [7].

3.4. Material issues in 3D printing of building components

Technology of Fused Deposition Modeling used in Canal House require material development. Finding appropriate material for this technology remains the biggest challenge, in building projects involving 3d technique. In Dutch project thermoplastic bio based material developed by Henkel was used. Nevertheless, Henkel is currently running some tests with a new developed eco-concrete that may be used in later stages of the Canal House project in order to increase compressive strength of printed pieces. For this phase of the project, building components, easy to join together, with gaps inside in a shape of honeycombs, were designed to be filled with special lightweight concrete assuring the insulation of the building, thanks to its air-entrained structure. Every element consists of numerous diagonal hollow columns that will support entire structure. A house will have 13 rooms printed on site and be assembled into one house. Another advantage of the building is the fact that all parts can be also separated, in case house needs to be relocated [4].

In Chinese WinSun project stereolitography printing used a mix of industrial wastes, fibreglass, cement and hardening agent. Developed material allowed to create building components layer by layer, like in ordinary 3D technology. Desired mixture needs to have maximum workability as well as maximum flowability in order to be easily placed in layers. The layers must ensure the bonding with subsequent layers at the same time. As the compressive strength is required the water content should be minimised while appropriate flowability is maintained [8]. The best describing word for the appropriate 3D cementitious mix would be thixotropic. The liquid state material should harden in appropriate time and before next layer is being laid. Engineers are working to find the best recipe for quick-setting concrete that will be manageable enough to be pumped out of the printer's nozzle and be as strong as reinforced concrete.

The possible material solution for 3D printing of building components could be sulphur concrete which is a composite material made of sulphur and aggregates (generally a coarse aggregate made of gravel or crushed rocks and a fine aggregate such as sand). The mix is heated above the melting point of sulphur ca. 140 °C [9]. After cooling the concrete reaches the target strength, without prolonged curing time like normal concrete. Sulphur concrete is considered as a potential building material for a lunar base shelters [10].

4. Preparation of computer models for 3D printing

So far we have discussed issues related to physical part of the manufacturing process. These are of course the key issues for the adoption of 3D printing technology. An important element is however also preparation of computer model for the parts to be manufactured. Fortunately, the level of 3D computer graphics both in terms of software and hardware makes it possible to build such digital models without much difficulties. It can be done using many commercial as well as Open Source software packages.

4.1. 3D Printing work-flow

The typical work-flow for 3D printing is illustrated in Fig.3. Firstly, a model is prepared in a 3D modelling application. Then it is exported to a file in a common 3D data exchange format. For 3D printing industry the most popular format is STL (Stereolithography) discussed below. Next, for the majority of 3D printing technologies the saved data is processed to decompose the model into slices. This results in a set of 2D contour lines that are further processed to generate control commands to position printing head or laser beams.

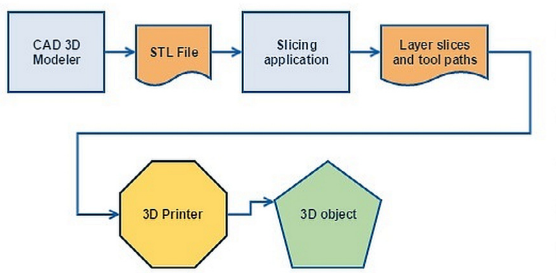
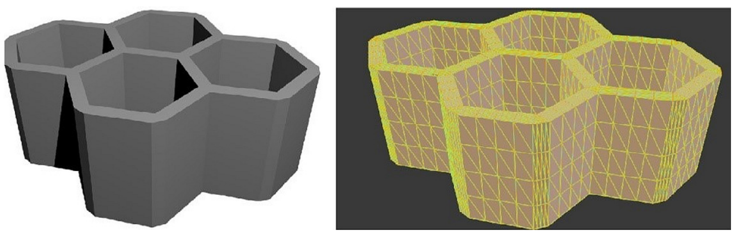


Fig. 3. Typical work-flow of 3D printing process.

4.2. STL data format

Transferring model data via STL format requires constructing a triangulation of all boundary surfaces as illustrated in Fig.4. This is most easily done if the solid model is build using B-Rep (boundary) representation, as for this representation the solid boundaries are stored explicitly within the model. The key element of exporting such representation to STL format is triangulation of curved surfaces. For CSG (Computed Solid Geometry) models, in order to save them in STL format, additional processing steps are needed to recover model boundaries.



a) b)

Fig. 4. (a) honeycomb; (b) honeycomb mesh.

While STL is a popular input format for 3D printing, it should be stressed that saving model in this format in not mandatory and the commands for controlling a printing process can be generated directly from model in its native representation. It is just the question of geometric computations within a geometric kernel of 3D printer. The current processing and data formats for geometric models for 3D printing have their roots in 3D computer graphics used for screen rendering. This can result in some difficulties and restrictions in using digital models for printing as discussed in the next point. It is worth to mention, that as additive manufacturing technologies mature and allow to produce very sophisticated, non-standard geometrical forms, there is also active research concerned new geometric representations that are related directly to the physical material deposition process. This allows to bypass the geometry processing that is suitable for screen rendering but problematic in case of 3D printing.

4.3. Preparing 3D models

As said above, in most cases in order to send digital model for printing it is enough to save it in STL format. Many 3D computer graphics programs can export models in STL. However, one should be careful using them, because many of these programs are designed to be used primarily for screen rendering of 3D models. It means that they can tolerate specific features of the models that are non-essential for rendering but that will be crucial for 3D printing. The main points to pay attention to are:

- 3D printing is a physical process contrary to screen rendering. Thus one has to obey physical constraints. Designing a model for printing one has to ensure that all elements of the model are physically realizable. This means for instance that free 1D edges and 2D faces are not allowed in the model;
- Printing is done in the presence of gravity. One has to consider stability of the model and the weight of its parts to avoid damaging printed parts, for instance by breaking to slender support elements;
- Some printing technologies require to design holes through which excess of non-bounded material can be evacuated;
- The boundary surfaces of the model must be watertight, that means all faces must be connected and have consistent orientation of surface normals. This is in order to distinguish in unique way model interior and exterior space;
- The triangulated surfaces must form a 2D manifold. In particular, all edges must be shared by exactly two faces, and there should be no singular points, where the boundary of the model touches itself. Example of non-manifold model is illustrated in Fig. 5.

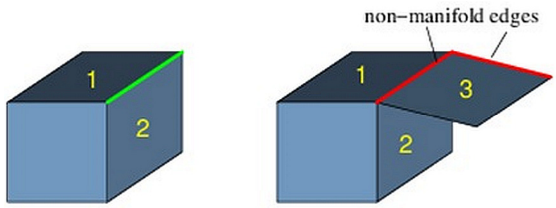


Fig. 5. Illustration of manifold (green) and non-manifold (red) edges of a 3D model.

4.4. Software

Autodesk Inventor is a software that allows to build complete 3D model of designed construction or device and enable to create planar drawing documentation for the project. While using Inventor, most of the time that constructor needs to put in a project is sacrificed for creative and conception works. All the changes made in a model are automatically transferred to the drawings.

In our investigations of digital side of 3D printing technology, we were primarily using Autodesk Inventor [11] and Blender [12]. Blender is open source package for 3D modeling, animations and computer games production.

Interesting feature of Blender is the export/import module for IFC models based on IfcOpenShell library. This module allows import and further processing of models prepared in BIM applications such as Revit [11] or Tekla [13].

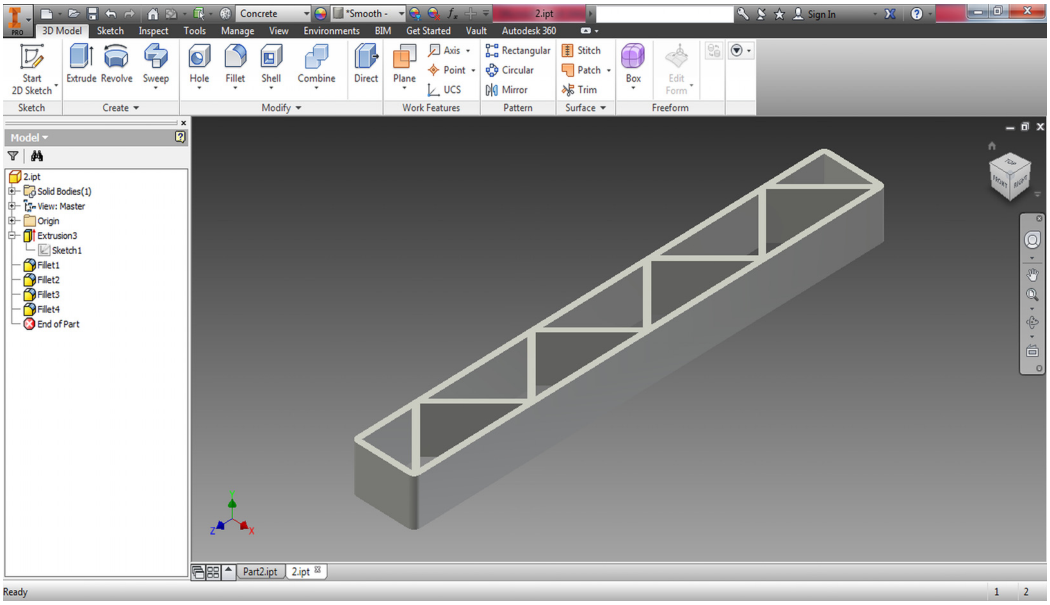
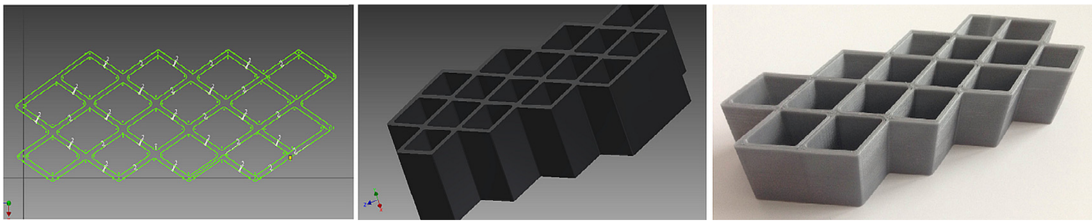


Fig. 6. 3D model of an envelope component developed by WinSun company and Autodesk Inventor software environment.

Two 3D models of building envelope components have been designed in Autodesk Inventor software. Replicas of the wall from the Canal House and WinSun houses were prepared and printed using ABS material (Acrylonitrile Butadiene Styrene) and using standard RepRap 3D printer.



a) b) c)

Fig. 7. (a) 2D sketch; (b) 3D model; (c) printed replica of a Canal House wall.

5. Conclusions

Technology of 3D printing is still young and presents lot of limitations, but there are high expectations and hopes for the future of 3D printed buildings and building components. Versatile applications of 3D printers and the development of new filament materials that could possibly ensure different properties to provide transparence, thermal insulation, or strength are under development.

The concept of contour crafting, allowing in-situ printing of dwellings may require the new architectural approach to building design. This technique will require development of new materials appropriate for 3D printing process, but also considering sustainability issues, materials in which traditional concrete ingredients will be replaced with environment friendly ones.

Creating the buildings with complicated shapes, may become one of the biggest advantages for most architects. Their imagination will be able to defeat previous obstacles related to limitation of traditional techniques of building. 3D printing may transform nowadays architecture, nevertheless, this technique should be developed taking into consideration sustainability issues both for material selection and construction method.

There are numerous advantages coming from developing 3D technology in construction and most important ones could be resumed as:

- Lower costs – the cost of printing construction elements of houses is much lower than traditional construction methods, also material transportation and storage on sites is limited;
- Environmental friendly construction processes and the use of raw materials with low embodied energy (i.e. construction and industrial wastes);
- Reduced number of injuries and fatalities onsite as the printers will be able to do most hazardous and dangerous works;
- Wet construction processes are minimized, so that building erection process generate less material wastes and dust compared to traditional methods;
- Time savings – time required to complete the building can be considerably reduced.

On the other hand, there is still a lot of anxieties that needs to be considered. The main unknown is, if developing the 3D printing technology will not take jobs from thousands of qualified workers.

It is hard to imagine so far that 3D printing could replace traditional construction in next few years. It is more possible, that both technologies will be present in the industry and 3D printing may be developed along with the traditional techniques, supporting them, especially in case of more sophisticated building projects.

As for the software an important issue will be ensuring interoperability of the applications used at the architectural design, structural analysis and printing process. In order of automate the building process to manage and optimize it, translation of the digital model and verification of its suitability for printing process must be done with minimal human intervention, most desirably fully automatic.

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