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3D Printing of Buildings: Construction of the Sustainable Houses of the Future by BIM

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Abstract

The paper presents the new technology of 3D printing of buildings for the sustainable houses of the future. 3D printing building technology is a new construction technique started with the invention of 3D printer. Latest 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. It has many 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 listed. Integration of Building Information Modeling with the 3D printing building technique are mentioned in comparison with the traditional construction techniques. Even though many advantages and benefits of this new technology, of course we have some concerns are summarized in the conclusions as the technology still has many limitations. A brief description of examples of 3D printing in construction industry are presented (Stupino town, Moscow, Russia - Apis Cor first company to develop a mobile construction 3D printer). Modeling a 3D model of building that will be appropriate for 3D printers is possible in many modeling software programs. One of the most popular formats for sharing such models is STL format common and it has been accepted by many proprietary software. Moreover, integration of BIM method with 3D printing modeling will be effective for energy efficiency, better design, cost reduction and isolation of structure.

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1. Introduction

3D printing is a process by which physical objects are created by depositing materials in layers based on a digital model. All 3D printing processes require software, hardware, and materials to work together. The first 3D printer was invented in 1983 by Charles W. and over the last decades, 3D printing has become one of the fastest growing technologies nowadays. In its early days, it was very complicated and expensive technology. Over the years, 3D printing started to be present in everyday life and printers became commonly used in industrial practice. 3D printing can also be referred to as 'additive manufacturing,' especially when referring to its use within a manufacturing setting, and many individuals will use both phrases interchangeably. As the technology continues to grow, 3D printing technology can be used to create everything from prototypes and simple parts to highly technical final products such as airplane parts, life-saving medical implants, automobile and even artificial organs using layers of human cells [1].

There are more ways to use this technology. The paper addresses the following research questions: "would the 3D printing technology be used in the in the future? And "Would the 3D printing building method replace traditional construction technologies?" and "Can we integrate it with BIM systems?".

2. The 3D Printing Technology and Materials Information

The starting point for any 3D printing process is a 3D digital model, which can be created using a variety of 3D software programs, for Makers and Consumers there are simpler, more accessible programs available or scanned with a 3D scanner. The model is then 'sliced' into layers, thereby converting the design into a file readable by the 3D printer. The material processed by the 3D printer is then layered according to design and process. As stated, there are a number of different types of 3D printing technologies, which process different materials in different ways to create the final object. Functional plastics, metals, ceramics and sand are, now, all routinely used for industrial prototyping and production applications. The different types of 3D printers each employ a different technology that processes different materials in different ways. Similar technique for 3D printing is selective laser sintering (SLS) that laser is used to melt particles of powder together to create an object. Materials used in the SLS technology usually have high strength and flexibility. The most popular ones are nylon or polystyrene [2].

The materials available for 3D printing have come a long way since the early days of the technology. There is now a wide variety of different material types, that are supplied in different states (powder, filament, pellets, granules, resin etc). Specific materials are now generally developed for specific platforms performing dedicated applications (an example would be the dental sector) with material properties that more precisely suit the application. Nylon, or Polyamide, is commonly used in powder form with the sintering process or in filament form with the Fused Deposition Modeling (FDM) process. It is a strong, flexible and durable plastic material that has proved reliable for 3D printing. Acrylonitrile Butadiene Styrene (ABS) is another common plastic used for 3D printing and it is widely used on the entry-level FDM 3D printers in filament form. It is a strong plastic and comes in a wide range of colors. Polylactic Acid or Polylactide (PLA) is a bio-degradable plastic material that has gained traction with 3D printing for this reason. It can be utilized in resin format for laser-based stereolithography (SLA) and digital light processing (DLP) processes as well as in filament form for the FDM process. It is offered in a variety of colors, including transparent, which has proven to be a useful option for some applications of 3D printing. However, it is not as durable or as flexible as ABS. LayWood is a specially developed 3D printing material for entry-level extrusion from 3D printers. It comes in filament form and is a wood/polymer composite [3].

2. 3 D Printing Applications in Building Industry

3.1 Office of the Future in Dubai

The 3D printed office was designed for the United Arab Emirates National Committee as the headquarter for the Dubai Futures Foundation. The so-called "Office of the Future" primarily serves as a meeting space for parties from all over the globe. The 3D printed office is a fully functional building featuring electricity, water and telecommunications and air-conditioning systems.The 3D printed house was produced in China. After the parts had been printed, they were shipped to Dubai. The project ultimately reduced labor costs by 50 % to 80% and construction waste by 30% to 60%. It is considered as the catalyst behind the construction 3D printing revolution happening in Dubai [4].

Fig. 1. (a) Side view of Office of the Future in Dubai; (b) Front view.

3.2 Apis Cor Printed House in Russia

A Russian company has done just, with a 400-square-foot-home being built from scratch in just 24 hours in Moscow. The cost of the building is $10,000, highlighting just how much potential the 3D printing technology has for the future. The house was built entirely on site using nothing but a mobile 3D printer, which makes all the results impressive. It is a house that is certainly habitable and short on space. The fact that it was produced at such low-cost in 24 hours. All the walls and foundations of this structure were printed with a concrete mixture and other parts such as windows, fixtures and furniture being added after construction. The house was finished with a fresh coat of paint with the final cost of the entire project totaling a modest $10,134 [5].

Fig. 2. (a) Front view of Apis Cor House in Russia; (b) Contour Crafting Process Apis Cor House.

4. BIM (Building Information Modeling)

BIM is a digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it forming a reliable basis for decisions during its life cycle, from earliest conception to demolition. (RIBA and CPIC) “a coordinated set of processes, supported by technology that adds value through creating, managing and sharing the properties of an asset throughout its lifecycle. An innovative and collaborative way of working that is underpinned by digital technologies which support more efficient methods of designing, creating and maintaining the built environment [6].

The construction industry has been facing a paradigm shift to (i) increase: productivity, efficiency, infrastructure value, quality and sustainability, (ii) reduce: lifecycle costs, lead times and duplications, via effective collaboration and communication of stakeholders in construction projects [7]. Building Information Modeling (BIM) seeks to integrate processes throughout the entire lifecycle [8]. If used appropriately, BIM can facilitate a more integrated design and construction process and generate substantial benefits. For instance, fewer design coordination errors, more energy efficient design solutions, faster cost estimation, reduced production cycle times and lower. BIM introduces a new work paradigm offering powerful perspectives for the integration and coordination of different domains and the processes involved in the design, construction and operation of buildings. The base schema for the BIM data is Industry Foundation Classes, an international standard for the exchange of BIM data, which provides a generic data schema covering among others architectural, building service and structural elements.

Building Information Modeling is an integrated process designed to generate and manage building data from design through construction. This process can also be used in building life cycle, maintenance, operations and cost analysis. The BIM process utilizes 3D software for increased project coordination and communication with multiple trades to provide a better end-product for the user [8].

It might be tempting to write 3D Building Information Modeling (BIM) off as a little more than 3D animation, 3D design, or 3D CAD. But unlike some other model-based processes, BIM has the promising potential to guide businesses by evaluation through every step of the construction process and even after construction is complete. According to the US. National Building Information Model Standard Project Committee, BIM is a “digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition.” [9].

BIM, meanwhile, is at the heart of the 3D printed building movement providing the software to govern the design and construction process. Austrian architect, Wolf D Prix, is pioneering the use of robots at one of his latest projects the Museum of Contemporary Art and Planning Exhibition (MOCAPE) in Shenzhen, China. Led by a BIM system, robots will mound and assemble, weld and polish the hyperbolic metal plates that make up the museum's irregularly curved stainless-steel center. Combining robots with the use of 3D-printed building components will make it much easier to create buildings with complex shapes, Prix said. It is quicker too he points out, "Normally this part of the building would take eight months with 160 workers on the site," said Prix. "Now we need eight workers on site, and it takes 12 weeks." With quicker construction, less labor, lower cost, as well as greater control and customization to create a leaner, greener, smarter building it's fair to say that the invention of 3D printed buildings, as Schmidt suggested, has made it easy to predict the future of construction.

Surprisingly, the construction industry has not changed much in the last 100 years. There are new things happening in mega-construction projects; larger skyscrapers, longer bridges and other huge structures; but not in day-to-day construction; that's pretty much stayed the same. Other than a few innovative materials and techniques, along with a greater reliance on power tools, home building is pretty much the same today, as it was 100 years ago. This might all be changing soon. 3D printing, which has been the realm of engineering test labs, may make a drastic change in the ways that our building structures are built. In recent years, 3D printers have moved out of the engineering laboratory, where they've been hidden for over 20 years, and are beginning to be used for other things. Artists have discovered this new medium, and yes, it's being looked at for construction as well [10].

Process of 3D Printing of Buildings Construction by BIM in Figure 3. A model is prepared in a 3D modeling application.

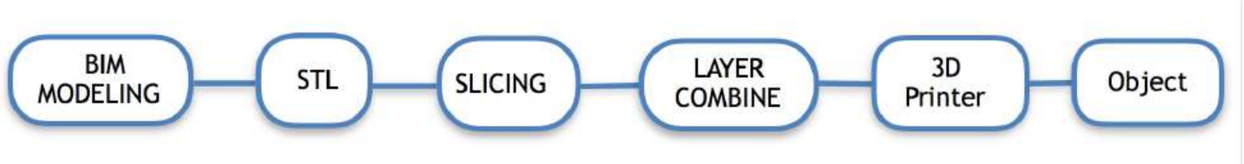

Figure 3: 3D Printing Process

5. 3D Printing Overcomes Construction Constraints

In the last decade, engineering research teams have been experimenting with using 3D printing to build components of buildings and entire homes, via 3D printing. The printing is done with what we could call "super-size printers", which use a special concrete and composite mixture. This mixture is much thicker than regular concrete, allowing it to be self-supporting as it sets.This opens up a whole new realm of possibilities for architects everywhere. Much like the freeform design of The Bird's Nest in Beijing, China, 3D printed architectural components are totally unfettered by typical design constraints. The ability to use curvilinear forms, rather than being cost and process limited to rectilinear forms, opens a whole new realm of design.

It is a commonly understood truth that rectilinear forms (rectangular forms) are one of the weakest structural forms imaginable. On the other end of the spectrum, the humble egg, which is totally curvilinear, is one of the most efficient structures in nature. A minimum of material, crafted into a shape where there are no straight edges, providing simple consistent curve, makes it the strongest structural design possible. 3D printing offers the practical possibility of using these curves in common structures [11].

6. What Is an STL File?

The STL file format has become the Rapid Prototyping industry's defacto standard data transmission format, and is the format required to interact with Quickparts. This format approximates the surfaces of a solid model with triangles. For a simple model such as the box shown in figure 4 (a), its surfaces can be approximated with twelve triangles, as shown in figure 4 (b). The more complex the surface, the more triangles produced, as shown in figure 4 (c).

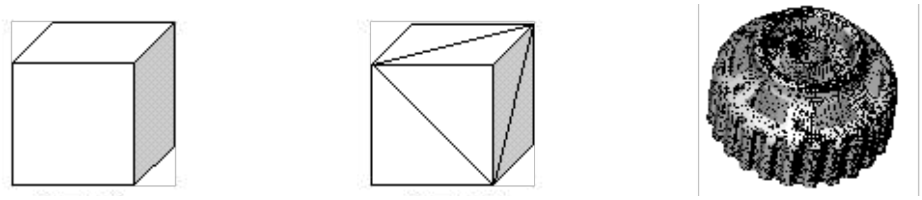

Figure 4: (a) (b) (c)

The triangulation (or poly count) of a surface will cause faceting of the 3D model. The parameters used for outputting a STL will affect how much faceting occurs (Figures 4 (a) and Figure 4 (b)). You cannot build the model smoother than the STL file. If the STL is coarse and faceted the physical 3D printed model will be coarse and faceted as well. However, the smoother/ less faceted your surface is, (the higher the poly count or triangulation) the larger your file. 3D printing can only accept a certain file size; therefore, it is important to find a balance between your model, its desired surface, and the 3D printing process of your choice.

STL means Stereo Lithography and can be exported into most CAD software suites, like Autodesk Fusion 360. For this reason, it has become the acronym" Standard Tessellation Language" [12]. The STL format only utilizes the three-dimensional description of the surface geometry without generating non-relevant information for printing like texture or color, leading to the popularity within the community [13]. Each triangle, which represents the surface, is characterized by three vertices and the related unit normal [14]. Since a prototypical 3D model is closed, also called waterproofed, each vertex is part of three or even more triangles. These redundant vertices are memory expensive even when they are stored in ASCII representation.

Most 3D printable models you can find on the internet are in the STL file format. The existence of this ecosystem, combined with STL-based software investments made by 3D printer manufacturers, has given rise to a large user-base that's heavily invested in the format [15].

7. SLICING

In the slicing step, the geometric model is intersected with parallel planes to obtain the contour of each material layer. We are not concerned in this paper with the selection of these planes they need to be known a priori. See Figure 5. This step can be done with a constant layer thickness (uniform slicing) or with variable layer thickness (adaptive slicing). Adaptive slicing provides better surface quality in critical features of the printed model while saving time in regions where rougher finish is acceptable [3].

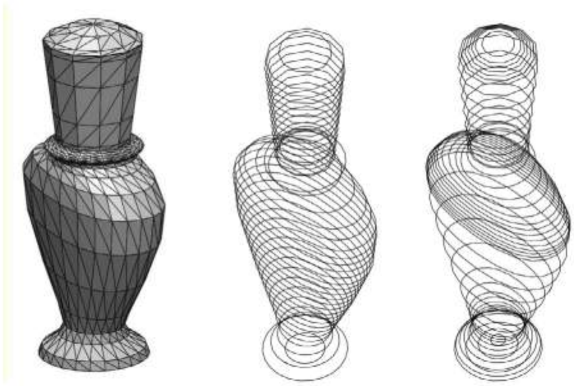

Figure 5: (a) (b) (c)

Figure 5: A triangle mesh of the surface of a 3D object model (a) and examples of uniform slicing (b) and adaptive slicing (c).

For greater generality, 3D printing software commonly assumes that the geometric model is reduced to an unordered and unstructured set of triangles that approximates the surface of the object. This representation is a de facto industry standard, embodied in the popular Stereo Lithography (STL) file format. Therefore, the primary result of the slicing step is also an unordered and unstructured set of line segments on each slicing plane [16].

8. Layer Combine

Combining different polymers in different combinations per layer of 3D printed material, is leading to the development of an entirely new palette of materials. Mixing materials is certainly nothing new. Samurai Swordsmiths knew that to make the famous katana swords used by its warriors, it needed to combine several steels in various layers to produce the curved blades that are hard, flexible and sharp. Getting the right mix of materials, in the right place, was a skill that was developed through the ages.

It's a philosophy that is perhaps unknowingly being applied to the modern day. As 3D print manufacturers expand on the multi-material capabilities of printers, many are looking to build up databases of 'meta-materials', known recipes that combine various polymers in different ways to produce very honed and specific properties, which are often quite different to the building block base materials used.

Among those carrying out this work is Hod Lipson, director of the Creative Machines Lab at Columbia University in the US. He says: "You can print flexible materials, optically transparent materials, biocompatible materials, hard materials and as this technology expands, we should expect to see more materials become available by blending different ones together."

The evolution of 3D printers is fast moving and a decade ago the technology was normally restricted to a single off-white soft plastic. Today, printers such as Stratasys' J750 allows six materials to be used at once, offering some 360,000 colors. It means that functional parts can be printed, for example scissors that are sharp enough to cut right away, materials that maintain heat can be used for injection moulding and real structural improvements mean parts are no longer flimsy but representative.

We are all intuitive about colors and know that mixing different colors gives you different shades. However, the ability to combine multiple materials, hard and soft, transparent and colored–layer by layer–to give rise to a huge range of new materials and properties, is not something that is currently thought about.

9. CAD tools still lacking for 3D print users

Topological optimization is fast gaining popularity as a tool to optimize the geometry of materials under particular load conditions. These tools are now becoming available with mainstream CAD packages, gradually, but other tools that engineers are asking for are not yet developed. “Software companies are behind the curve on this, CAD companies need to do more to keep up,” says Hod Lipson, director of the Creative Machines Lab at Columbia University in the US. “Software is holding up exploring the true potential of 3D printed parts and meta-materials [17].

Potential Implications of 3D Printing for the Home Building Industry

Although still in its early days, 3D printing could offer the following benefits:

- Onsite or factory applications.
- Printed products only use as much material as needed to form them. This means fewer resources are required and less waste is generated.
- Reduced transportation costs if products are printed on-site (although the cost of transporting the printer can be expensive due to the size of printers currently needed for construction).
- Potential to create more efficient and interesting designs as 3D printing can achieve shapes that conventional techniques cannot.
- Lower labour costs.
- Reduced cost of customized design (with 3D printing, it costs the same to create one item as to produce thousands.)
- Reduced health and safety risks if 3D printing can be used to produce assemblies that would otherwise need special equipment and precautions to be taken.
- Current challenges to be overcome include:
- More expensive than conventional construction due to high cost of 3D printer and lack of familiarity in the industry with 3D printing technologies and applications.
- Currently, a limited number of materials have been used, although experimentation is underway with printers capable of using multiple materials to produce more complex assemblies.
- 3D printers can be large and, therefore, difficult and costly to place on site.
- 3D printing incurs more up-front costs to create the digital model that will result in safe, cost-effective products.
- Printers are currently slow compared to conventional construction, although they can be operated 24 hours a day, seven days a week.
- The potential of a disruptive impact on the type of skills and labor needed to design and build homes [18].

10. The Future of 3D Printing in Residential Construction

There is a wide range of views about where the technology could be headed. Although 3D printing is still in its early days in all industries, the potential benefits seem to be driving the technology forward. Some suggest 3D printers will be used mainly to print building components and panels either in factories or on site, while others envision 3D printing as a transformative technology that could revolutionize the construction industry [19].

11. 3D Printing of Buildings for Construction of the Sustainable Houses

3D printing technology to use building will be increase sustainability. Houses can built based on the material life cycle, that can be used in evaluating the environmental sustainability of building materials. 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 [20].

Conclusions

There are different technologies for 3D printing system and we realize that BIM is also one of the synchronizing equipment for 3D print system and foe future plan and calculation of the building will be automatically defined by BIM so benefit of the BIM will be future plans of society and building economically income and outcome. To use BIM also can be improve the design details and accuracy of the designed buildings and plan of action will be more specified by using BIM detailed system. 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.

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