Some new technologies and materials for 3D printing

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Abstract: Three-dimensional printing (3DP) in building industry has a number of important advantages, such as creation of various geometric forms without the need for molds, the ability to create complex elements, the possibility of automation, speed and a low amount of waste, the use of innovative materials, construction in layers of different materials, and more. So, 3DP is an effort to put digital manufacturing into practice, enabling a direct transition from building design / modeling (BIM) to 3DP.

One of the important limitations in 3DP is the materials. Because printing is done in layers, it is important to take into account the hardening time of the material and its ability to stick to create a uniform structure. Another problem is the tolerance of the material to different types of solidification: melting, pressing. That's why there are methods for combining iron or polymer reinforcement.

There are combined methods: 3D printed elements are used as prefab elements to make the building process more effective.

This industry is one of the fastest growing manufacturing technology sectors covers all markets from aerospace and healthcare to construction and consumer products.

This article provides some aspects of application in construction, materials and their compositions, as well as examples of the use of 3DP at buildings, structures, etc.

Keywords: 3D technologies in civil engineering and construction, materials for 3DP, 3D concrete printing, concrete polymer reinforcement, dispersive reinforcement concrete.

General historical analysis

3D printing technology originated in the 80s of the 20th century, but construction 3D printing appeared much later. The first construction projects using this technology appeared only in 2014. We are talking, first of all, about the so-called small architectural forms (benches, flower beds, fences). They did not even dream of building houses. But already in 2015, the Russian startup Apis Cor made a splash - it printed a whole house in the Moscow region. Since then, news about new 3D printed houses has periodically appeared. However, despite the fact that the technology proved to be very promising in terms of the speed of construction of housing and the reduction in the cost of construction, no mass implementation followed. In 2014 - 2016 the first samples of building 3D printers and prototypes of printed buildings appeared. The concepts of various form factors of construction 3D printers and types of printing materials were tested. In 2017-2018, the world made the first notable investments in a number of 3D printing construction start-ups. Further, by 2020, these investments “rolled” in the form of reaching a certain level of technological maturity - the first commercial products (3D printers and houses) appeared.

Finally, in 2020-2022, it became clear that the hypotheses about the effectiveness of construction 3D printing were justified (cheaper, faster, more environmentally friendly), and large investments began in the industry. A prime example is GE's investment in Danish COBOD or the US company ICON's $2 billion capitalization. In 2022-2023, more than 1,000 buildings will be printed around the world, from individual buildings/pilot projects to entire villages and large facilities. infrastructure. In addition, in a number of countries, a regulatory framework has already been created or is being actively created for the introduction of additive technologies in the construction industry. Thus, I believe that this period of time is a fairly natural cycle of technology development, which is expected to grow exponentially in the next decade. According to a Research & Market report, the global construction 3D printing market was valued at $354.3 million in 2022 and is expected to reach $11,068.1 million by 2027, up 99.04%.

Without going too deep into the technology, we can say that construction 3D printers are very similar to classic FDM / FFF printers that print with plastic, only instead of plastic, the material here is a cement mixture that is fed directly into the nozzle and forms an object by layering. Printers are also portal, based on a “crane arm”/manipulator. “The breakthrough” came when in the summer of 2021, the American company ICON, which was trying to introduce 3D printing into the construction of various auxiliary facilities, signed a contract with one of the largest American developers Lennar to build a village for 100 people. home in Texas and immediately became a unicorn, receiving $200 million in investments from several investment funds. At the same time, the Danish company COBOD, set up by the world's largest construction formwork company PERRI, began selling its gantry construction 3D printers as well as participating in construction projects around the world.

So far it has been only about wall printing. Everything else (foundation, windows, doors, ceilings and roof) is done in the traditional way. 3D printed walls are built as permanent formwork, which greatly saves the amount of cement used, which in turn reduces construction costs and reduces the environmental impact of cement production. In addition, with this method of construction, no additional waste is generated, and the strength of the structure does not suffer. It can be reinforced and engineering communications can be laid immediately, which also affects the final speed of the construction of the object.

This reduces the overall weight of the structure, the remaining cavities can be filled with lightweight foam concrete, insulation, straw or any other available material. For such a lightweight construction, a lighter base can be used. The construction method itself is more economical in terms of material, and therefore environmentally friendly. Another startup, Mighty Buildings, headquartered in California, initially relied on a polymer with the addition of mineral chips. And while the company doesn't build entire homes, it only makes wall panels, it has won numerous design awards and has also received a $400 million valuation in multiple investment rounds.

The total savings on building walls can be up to 30%, and the total cost of the house can be reduced by 10%. This is true for houses intended for conventional construction. And if you initially design using 3D printing, then this ratio can be improved by optimizing the laying of communications, the ability to immediately print interior walls, laying niches for bathrooms, fireplaces, built-in wardrobes and kitchens, as was done in the built COBOD house in Germany.

3D PRINTED TECHNOLOGY AND MATERIALS

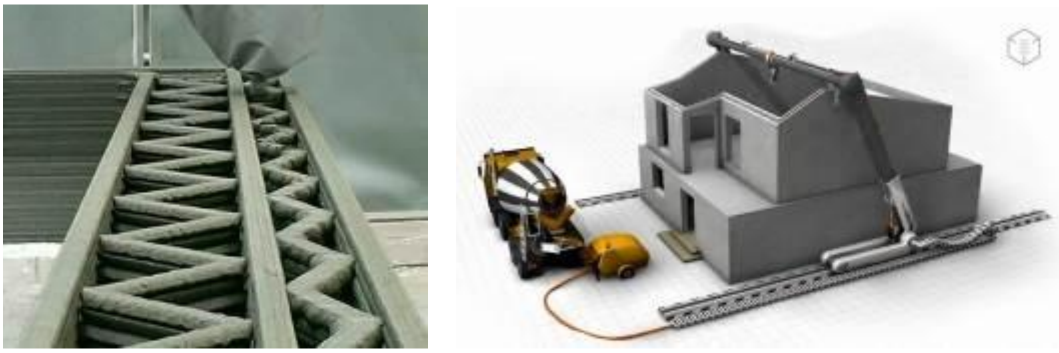
We have published several articles on the subject. One of them has recently been published in China (2023) [1].

In general, the three-dimensional construction can be described in the following process: automatic printing in layers (material adapted to the purpose, the type of product and the process) using a computer-controlled machine.

Materials for 3D printing and their properties are of significant research interest.

Building materials printed on a 3D printer must have exceptional printing speed. This includes the possibility of pumping, extrudability, ability to assemble.

Recently, 3DP has been developed as an attempt to put digital manufacturing into practice, enabling a direct transition from building design/modeling (BIM) to 3DP printing production. The technical part of the transition from BIM to print is already largely automated [2,3].

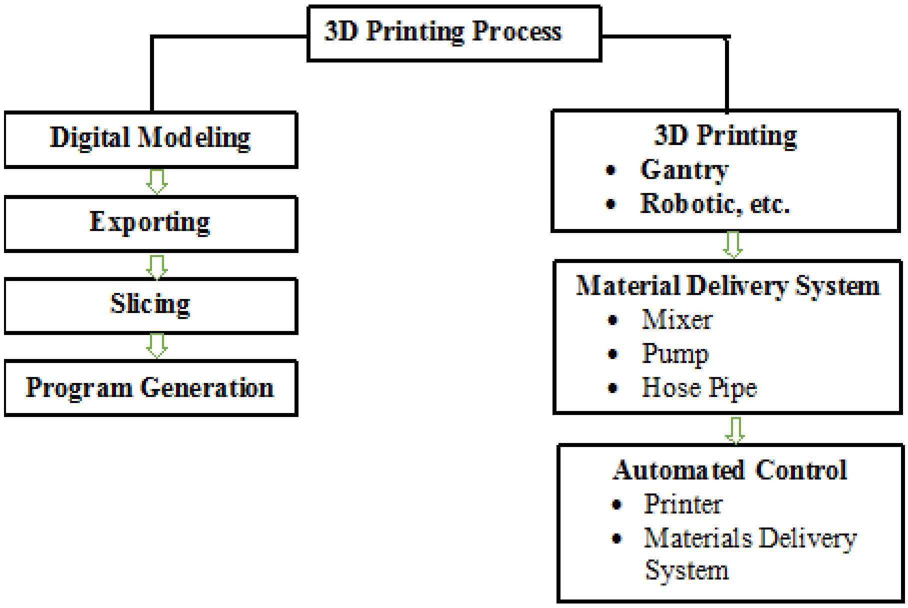


PIC. 1: 3D PRINTING PROCESS [2].

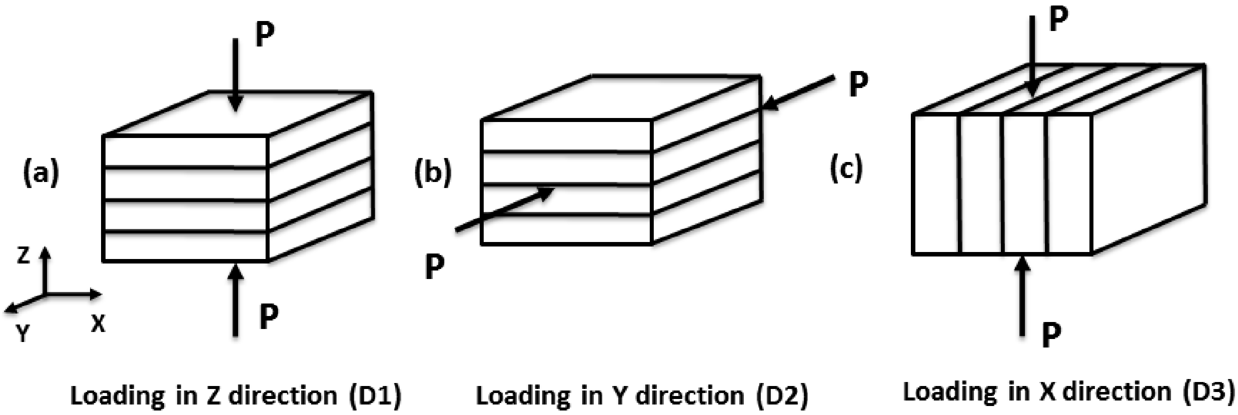
In general, the process using the 3D printing method in all its stages and components can be described by the scheme shown in fig. 2.

The thickness of the printing layer and the minimum time between layers will depend on the viscosity of the concrete and its initial hardening time.

These parameters can be determined by the additives to the concrete.



PIC. 2: 3D PRINTING PROCESS STAGES.



PIC. 3: APPLICATION OF COMPRESSION LOAD IN PRINTED OBJECTS RELATED TO THE PRINTING DIRECTION

For example, some 3D printing patents:

- The invention relates to a dry mineral binder composition comprising cement and mineral fillers for the manufacture of molded parts by way of 3D printing (MX2021010729 (A)).

- Multi-component mortar system (US2019276364 (A1)).
- A method for 3D printing of mineral binder compositions (WO2019030255 (A1)).
- A device for transferring concrete materials for novel 3D printing (LU102606 (B1)).
- Low-shrinkage 3D printing concrete co-doped with lignin fibers and preparation method of low-shrinkage 3D printing concrete (CN113372074 (A)).
- System used to measure and allow any correction of the viscosity of the printing material during 3D printing or a vertical construction process, where it can then be thickened and/or accelerated to improve print speed and quality (WO2023102272(A3)).
- There are discharge devices that allow printing at the desired rate (e.g. rotary discharge (CN219060914 (U)).
- The invention discloses light-cured 3D printing resin concrete and a preparation method thereof (CN115926382 (A)).
- The invention relates to the technical field of building materials, in particular to 3D printing lightweight concrete that includes rubber powder and a method of preparing lightweight concrete for 3D printing (CN115872703 (A)).
- The invention relates to the technical field of building materials based on cement, in particular to 3D printing of desert sand concrete with high ductility and its preparation method (CN115893959 (A)).
- The invention relates to the technical field of cement-based materials, in particular to a cement-based material interface strengthening material as well as to its preparation and application method, and a cement-based material interface strengthening material (CN115745470 (A)).

- A method of preparing artificial test samples imitating natural rock samples, which includes steps: on-site sampling; 3D sample scan of the rock mass; model design; creating a template; 3D printing. The present application can effectively optimize the accuracy of the rock mass experiment (AU2022221559 (A1)).
- Describes a concrete composite beam for 3D printing, and belongs to the technical field of 3D printing. (CN115749128 (A)).
- The invention relates to the technical field of chemical building materials, in particular concrete for 3D printing suction and its preparation method (CN115710111 (A)).
- The service model reveals equipment for transferring concrete materials for 3D printing with a stirrer structure, which relates to the technical field of 3D printing of cement products (CN218234376 (U)).
- The present invention discloses a construction method for a spatially printed 3D reinforced concrete structure. The construction method effectively improves the mechanical performance of the concrete structure cavity, and improves the tensile strength and crack resistance of the concrete structure cavity (US2022402164 (A1)).
- The invention belongs to the technical field of solid waste treatment, and specifically refers to a cement-based 3D printing material using solid waste, as well as to a method of preparation and application of the cement-based 3D printing material (CN115466090 (A)).
- The invention relates to a construction method of a 3d printing wall decoration composite material acoustic panel (CN115434441 (A)).
- The invention belongs to the technical field of building materials, and particularly relates to an alkali-activated 3D printing concrete material based on modified attapulgite and preparation of the alkali-activated 3D printing concrete material (CN115368093 (A)).

- The present invention relates to granular composite density enhancement, and related methods and compositions. The applications where these properties are valuable include but are not limited to: additive manufacturing (“3D printing”) involving metallic, ceramic, cermet, polymer, plastic, or other dry or solvent-suspended powders or gels; concrete materials; solid propellant materials; cermet materials and etc. (US2022395898 (A1)).

MATERIALS

Consider the latest construction innovations in recent months. Concrete is the most common building material, but alternatives with various improved characteristics have recently begun to appear. Engineers in the US have come up with yet another form of concrete, a lightweight, multifunctional product that suits a variety of building types and can even generate its own electrical charge.

At the same time, for the construction of structures with the same strength characteristics, it requires 15% less. The metamaterial, created by researchers at the University of Pittsburgh, consists of a reinforced polymer lattice coated with an electrically conductive cement mixture. The concrete, in which the graphite powder is mixed, becomes an electrode, and a mechanical trigger creates a contact electrification between the layers. There is not enough energy to supply it to the power grid, but enough to monitor the appearance of cracks in concrete structures with its help. The metamaterial itself can be customized for various construction tasks, changing its flexibility, shape and fragility. In testing, it withstood a 15% volume reduction without compromising structural integrity. A lightweight, flexible concrete-based metamaterial could, as envisioned by the inventors, find use as a shock-absorbing material for airport runways or structures that protect against seismic shocks, as well as become the basis of highways that will drive and on which electronics will depend.

A bit of fantasy, but also with earthly possibilities: British scientists have presented a new recipe for making concrete from Martian or lunar regolith, potato starch and salt. StarCrete material proved to be much stronger than conventional concrete grades and can become the basis for the construction of habitable bases on neighboring celestial bodies. Before opening permanent bases on other planets, you need to decide what to build them from. It is too difficult and expensive to transport tons of materials from Earth, so scientists and engineers are developing methods that will use local resources for this.

A new such technology was recently introduced by the team of Aled Roberts from the University of Manchester. Their StarCrete material is made from Martian soil simulant, starch and a small amount of salt. Laboratory tests have shown that its compressive strength reaches 72 megapascals - about twice that of the most common grades of conventional concrete. When using not Martian, but lunar regolith, the strength already exceeds 90 megapascals. Roberts and his colleagues have been dealing with the problem of “foreign” concrete for years. Some time ago, they demonstrated a very unusual material that uses human blood plasma as a binder. Its compressive strength reaches a quite acceptable level of 40 megapascals, but, of course, requiring astronauts to constantly donate blood for the sake of construction is not a good idea. Therefore, since then, scientists have been looking for a more convenient bundle for the Martian and lunar regolith.

Most of the food for future colonists is expected to be locally grown, with the potato considered one of the most promising foods. Roberts and his co-authors showed that the starch contained in potatoes can be an excellent substitute for albumin in the production of "alien" concrete. According to scientists, 25 kilograms of dried potatoes are enough to produce about half a ton of building material.

In terms of a standard brick, this is more than 210 pieces, and about 7.5 thousand are required to build a three-room house. In addition to the filler (lunar or Martian regolith) and binder (starch), the StarCrete formula includes a small addition of magnesium chloride, which significantly increases the strength of the finished material. This supplement was present in previous work by the Roberts team, where they used blood plasma, and proposed to obtain magnesium salt from tears.

Now scientists note that it can be mined directly from the local soil. Manchester-based startup DeakinBio will improve and commercialize the new technology. They expect the recipe to find applications outside of space. Adapted to earth conditions, it will provide greener materials for construction and reduce carbon emissions associated with the production of conventional cement and concrete [4,5].

3D printing is a technology for creating objects, commonly referred to as "additive manufacturing", which consists of compounding material layer by layer to obtain objects from 3D models or other computer data source [6,7]. In particular, under the control of a computer with the help of an industrial robot, successive layers of material are formed. For example, analysis of patent documents of the Russian Federation according to the fips.ru database for the keywords "3D printing", "3D printer", "additive"[8].

Of the 530 documents, the overwhelming majority were patents of the Russian Federation for inventions (63%). In second place are patents for utility models (21%). Surprisingly, there are quite a lot of computer programs for such a young industry, 75 units. As expected, there are few databases on AT (here it should be emphasized, which is explained by the fact that AT is relatively little introduced into civil economic activity). Approximately 2/3 of patents and certificates belong to residents of the Russian Federation, and the rest - to foreigners, 99% from far abroad countries, mainly from Western countries and China. There are 334 patents of the Russian Federation for inventions. Residents of the Russian Federation own 242 patents.

In construction, 3D printing is carried out “live”, in the fresh air, and not in closed boxes and sealed installations. It is necessary - due to fluctuations in temperature, humidity, wind and sun - to solve the conflicting problems of print speed and solidification stability of the material. The main physical and chemical problem is the rheological properties of the building material for 3D printing [9,10].

In practice, 4 types of additives are added to ordinary cement mortar:

1) rheology modifiers of the working mortar / dough,

2) concrete setting accelerators,

3) water demand regulators,

4) anti-foam additives.

3D printing of structural materials is a continuous process that involves transporting freshly mixed concrete or mortar to an extrudable matrix and applying the structural material through the outlet (nozzle) of the matrix to form a layer of concrete. When placing concrete or mortar, the paving head moves under the control of a computer device to create a layer of structural material according to the underlying 3D model. In order for the freshly prepared concrete or mortar to pass through each section of the conveying process to the laying head, it is necessary to ensure stable rheological properties of the freshly prepared material [4,5].

However, the structural material must not only be fluid enough to serve the purposes of transport and extrusion, but also rigid enough to provide the necessary mechanical stability for the 3D printed structure before the hydraulic binder hardens. In particular, the lower layers of the structural material must withstand the loads imposed by the upper layers without failure. The team of Rustem Mukhametrahimov of the Kazan State University of Architecture and Civil Engineering demonstrates high inventive activity (about 20 patents for the composition of building mixtures and methods of building 3D printing over a five-year period). So, patent No. 2777886 relates to a building mixture, including Portland cement, quartz sand, Relamix PC superplasticizer in the form of a copolymer based on polyoxyethylene derivatives of unsaturated carboxylic acids. The technical result is an increase in dimensional stability and ensuring the absence of defects in the form of gaps in the printed layers, a decrease in shrinkage deformations and an increase in the tensile strength of cured composites printed on a 3D printer.

About 10 patents were received by prof. Galina Slavcheva with co-authors from the Voronezh State Technical University. In particular, invention No. 2729085 relates to building materials adapted for building 3D printing modes. The patent protects the two-phase mixture. Of interest is the invention No. 2739910 prof. Valentina Poluektova from the Belgorod State Technological University. V.G. Shukhov. It refers to a polymer-cement dry mortar for 3D printing, including Portland cement, polymer binder, sand, fiber and modifier. As a polymer binder, a redispersible polymer powder of polyvinyl acetate or polyvinyl acetate copolymers is used. The analysis of patents and the experience of their practical use gives reason to conclude that the active introduction of additive technologies for the production of building materials into construction practice promises to reduce the time and cost of construction, reduce the metal consumption of monolithic structures, and also creates the possibility of optimizing the area of residential, public and industrial buildings due to greater flexibility in the choice of space-planning solutions. This type of construction forms a new industrial niche for the production of promising materials for additive construction production based on modified hydrate-setting mortars.

Engineers have developed a material that can be programmed to control heat transfer. This can save up to 40% of the energy used to cool homes. Researchers at the Fraunhofer Institute for Programmable Materials have developed programmable thermal insulation for homes that can replace air conditioners. Porous foam (can be used in 3D technology) seals the room on hot days and circulates air at night. The developed material is a foam construction with unusual properties. The principle of its operation is that when the sun is shining and it is very hot, the foam elements expand, thereby hermetically closing the ventilation slots between the wall of the building and the cladding. As a result, the room temperature remains cool. At night, the foam contracts and opens up the vents, allowing fresh air to circulate behind the cladding and effectively cool the home.

During the manufacturing process, scientists can tune how the foam changes shape and at what temperature. In addition, unlike classic shape memory foams, the new material can change shape many times, opening and closing pores over and over again. The researchers note that this development is suitable not only for residential buildings. By combining various elements, it is possible to control the temperature regime in production. To do this, it is enough to use a similar thermal insulation foam, temperature-controlled pipes that dissipate heat when the temperature rises above the set temperature, and a programmable material that can store heat when it is too hot and release it when the temperature drops below the set one. The researchers note that new materials have great potential. Only when used in ordinary residential buildings, thermal insulation saves up to 40% of the energy used to cool houses. Combined with elements that store and return heat, this will also help eliminate some of the heating in the future.

According to Market Analysis Report [11], the global 3D printing market size was valued at USD 16.75 billion in 2022 and is projected to grow at a compound annual growth rate (CAGR) of 23.3% from 2023 to 2030. The aggressive research

& development in three-dimensional printing and the growing demand for prototyping applications from various industry verticals, particularly healthcare, automotive, and aerospace & defense, are expected to drive the growth of the market.

CONCRETES AND NANO-ADDITIVES

The HTTM CO RAN proposed to replace the base in cement binders with a silicate one. It will improve the quality of the material used: heating at a lower temperature during manufacture, higher compressive strength, no swelling when heated.

Replacing conventional rebar with basalt rebar. Such fittings are lighter, radio-transparent and resistant to corrosion compared to conventional ones. The shock-resistant characteristics of such reinforcement increase by 4.5 times, and the durability by 5 times.

Various nanostructured additives to concrete: For example, 0.1% Kemerit in the total cement mass of such an additive will increase the strength of structures by 25%.

CONCRETE AND DISPERSED REINFORCEMENT

The development of promising concrete mixtures that can withstand the action of external loads is an important scientific problem of modern construction.

Various types of dispersed reinforcement are being developed and introduced. These developments include mathematical planning methods and experimental tests. A 35% increase in compressive strength was obtained in fiber-reinforced concretes made using a combination of steel and basalt fiber with a volume concentration of 2% steel fiber and 2% basalt fiber.

The maximum bending strength increased by 79%, the ultimate strain in axial compression decreased by 52%, the ultimate strain in axial tension decreased by

39%, the modulus of elasticity increased by 33%. Similar results were obtained for other combinations of dispersed reinforcement. The studies carried out made it possible to determine the most effective combinations of fibers of various types of fibers among themselves and their optimal volume concentration.

SELF-HEALING MATERIALS FOR 3D PRINTING

Researchers at Imperial College London have created three-dimensional building blocks that can self-repair after damage. They later found a method to use this technology in 3D printing.

Engineered Living Materials (ELM) harness the ability of plants to heal and replenish material and can respond to damage in harsh environments with a "sense and reaction" system.

The journal Nature Communications published that this could lead to the creation of new materials that detect and heal damage. By integrating building blocks into self-healing building materials, scientists want to reduce maintenance and extend the life of the material.

The same technique is used in architecture, for example as modular elements that can be assembled into various building structures.

To create the ELM, the researchers genetically engineered a bacterium called Komagataeibacter rhaeticus. This is to get them to produce fluorescent 3D sphere-shaped cell cultures, known as spheroids, and equip them with damage-detecting sensors. They built spheroids into various shapes and patterns, demonstrating the potential of spheroids as modular building blocks.

PROCESSES

3DP was originally developed for the production of small, complex, low volume products and was known as fast modeling.

Over the years, several large-scale technologies have been developed to enable 3DP designs and applications. For example, the use of mobile robots for large scale and parallel 3DPs on concrete structures.

Currently, there are many examples of 3DP technologies that are under development and testing. For example, printhead configuration, printer kinematics, print strategy.

ECONOMIC ASPECTS AND TRENDS

Undoubtedly, the demand for mass construction in construction will create a need for 3DP, new and more economical technological solutions will appear.

3DP has enormous design potential and can be used to build buildings with complex shapes or in special conditions. In the future, with the popularization of this technology, private consumers will also be able to complete their homes. 3DP also has great development potential in the field of individual interior design.

Some known today conditions of introduction 3DP: The first condition is time. It takes more time to get a better surface quality, which increases the time cost. The second condition is the cost of optimization. Any optimization process will increase the cost due to additional design work and the structure may become unnecessarily complex.

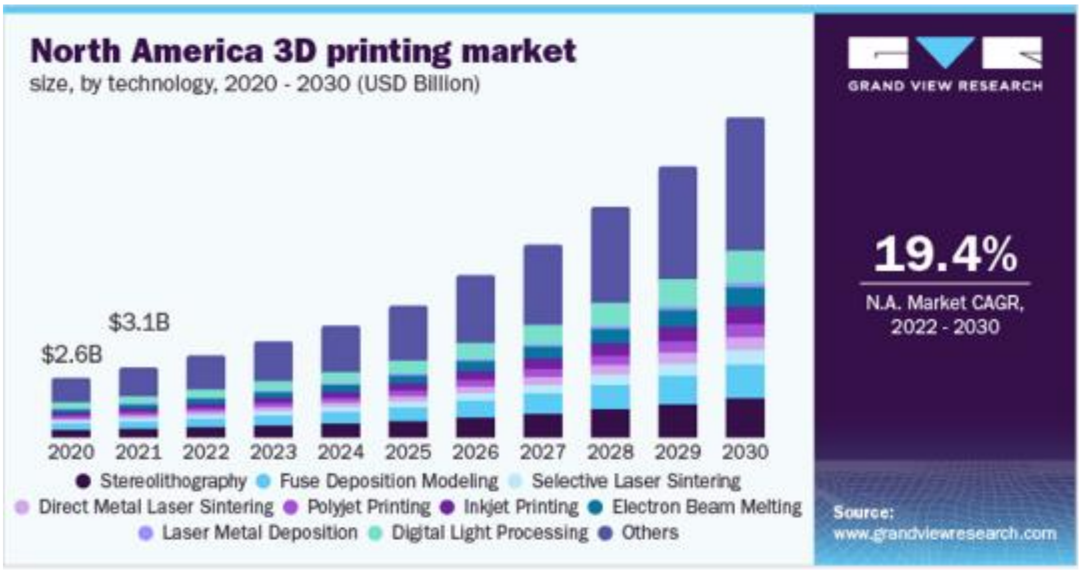
To measure whether a 3DP can reduce costs, it is necessary to assess the financial performance of a building product throughout its entire life cycle.

Further empirical research is needed to evaluate the life cycle cost of 3DP in raw materials, printing systems, process optimization. This is to determine how to select theoretically efficient and economical technologies.

SOME OF THE WORLD'S LARGEST 3D PRINTING COMPANIES BY MARKET [11,12]

3D SYSTEMS (NASDAQ: DDD), MARKET CAPITALIZATION: $2.2B

3D Systems is the most valuable and biggest 3D printing companies in the world, with a market capitalization of $2.2 billion. The company sells a variety of items, including 3D printers, printing materials, digital design tools, and more. Manufacturing, 3D scanning, and healthcare are among the industries where the company's 3D printing services are used.With the acquisitions of Titan Additive and Kumovis, it is now expanding into extrusion-based 3D printing technologies.



PIC. 4: NORTH AMERICA INVESTMENT IN 3D PRINTING TECHNOLOGY

XOMETRY INC. (NASDAQ: XMTR) [12], MARKET CAPITALIZATION: $2.17B

Xometry, which debuted on the stock market less than a year ago in June 2021, is now second on the list of the top 3D printing companies. Xometry is an on-demand manufacturing company that was founded in 2013 as a convenient marketplace for products people to make and use. Xometry digitised manufacturing by starting from 3D printing but expanding to include much of the conventional manufacturing processes as well. Today, it is one the world's biggest on-demand manufacturing platform. To understand Xometry better, think of it as the Airbnb of On-demand manufacturing.

STRATASYS LTD. (NASDAQ: SSYS), MARKET CAPITALIZATION: $1.55B

Israel-based Stratasys is on the third spot in the list of world's largest 3D printing companies as per market capitalisation (rising from 5th position last year to the third position). It also ranks high among the biggest 3D printer companies across the world. With a market cap of $1.55 billion, the company is undeniably a force to be reckoned with in the global 3D printing market.

PROTOLABS (NASDAQ: PRLB), MARKET CAPITALIZATION: $1.51B

With a market cap of $1.51 billion Protolabs stands fourth in the list of largest companies in the global 3D printing market. Specialising in rapid prototyping, the company is known to offer the fastest source for and customised custom prototypes production parts. The company uses three additive processes namely stereolithography, selective laser sintering (SLS), and one of the metal 3D printing technologies such as direct metal laser sintering (DMLS). With more than half a dozen manufacturing locations across three continents, the company is known to produce and assemble custom parts in just one day.

VELO3D INC. (NYSE: VLD), MARKET CAPITALISATION: $1.47B

Velo3D is a new entrant to the list as it debut as a publicly-traded company in October 2021. Velo3D is a leading additive manufacturing technology company for mission-critical metal parts. It has quickly rose to prominence due to its proprietary Sapphire® system. Velo3D's reputation can be gauged by the fact that its AM systems are used by some of the most innovative companies in the world, including SpaceX, Honeywell, Boom Supersonic and more. Velo3D is said to be effective in producing mission-critical parts and that too at fraction of time and cost required by conventional technologies.

DESKTOP METAL INC. (NYSE: DM), MARKET CAPITALIZATION: $1.27B

Desktop Metal became a publicly listed company on December 10, 2020 after going through a SPAC deal. There was much excitement as Desktop Metal went public but for multiple reasons the DM stock has continued to fall. From the stock hitting an all-time high of $35 per share last February, it has plummeted to $4 per share (March 3rd, 2022).

Though the picture seems dark, Desktop Metal is betting big on its flagship Production System P-50 printer. The company shipped its first P-50 printer on 28th February. So, there is something to look forward to.

MATERIALISE N.V. ADR (NASDAQ: MTLS**),** MARKET CAPITALIZATION: $1.17B

With a market capitalisation of $1.17B, Belgium-based Materialise NV comes at number seven this year. The company has more than two decades of 3D printing experience and offers a host of software solutions and 3D printing services to a variety of industries such as automotive, art and design, consumer goods, and healthcare.

The Materialise stock is steady at $19 per share. Though it reached a 52-week high of $77 per share in February last year, but has seen a downturn since then.

NANO DIMENSION (NASDAQ: NNDM), MARKET CAPITALIZATION: $890.02M

Israel-based Nano Dimension is the next on the list of the world's largest 3D printing companies with a market cap of $890.02M. The company has registered exponential growth recently and has emerged as a leader in additive electronics and nanotechnology-based ink products. Its products include the award-winning DragonFly Pro 2020 3D printer known to 3D print a variety of functional electronics such as sensors, antennas, moulded connected devices, printed circuit boards, and other devices. By easing the process of manufacturing such complex electronic devices, the DragonFly 2020 Pro 3D printer is transforming the electronic additive manufacturing market and allowing companies to take charge of their entire development cycle.

MARKFORGED HOLDING CORP. (NYSE: MKFG), MARKET CAPITALIZATION: $691.37M

Markforged is an American public additive manufacturing company that debuted on the NYSE last year in July 2021. It designs, develops, and manufactures The Digital Forge — an industrial platform of 3D printers, software and materials that enables manufacturers to print parts at the point-of-need.

Markforged was valued at $2.1 billion at the time of its debut but has seen a downfall in stock prices like almost every 3D printing company and especially those going public via SPAC deals. One of the reason for the fall in prices is likely due to the SPAC deals going out of favour among many other.

SHAPEWAYS HOLDINGS INC.: (NYSE: SHPW), MARKET CAPITALIZATION: $155.51M

Shapeways is the Dutch-New York counterpart of the Belgian Materialise. It is a digital manufacturing platform offering customers access to high-quality part manufacturing from a wide selection of processes and materials through automation, innovation and digitisation.

It also offer ready-made products from its marketplace like an E-commerce store catering to B2C clients who can place an order and get it delivered to their doorstep.

MEATECH 3D LTD. (NASDAQ: MITC), MARKET CAPITALIZATION: $82.49M

MeaTech3D is also among the biggest 3D printing companies in the world. MeaTech 3D Ltd. is an Israeli food technology company, that promotes and focuses on developing alternative option to industrialised farming. It does this to circumvent the ethical and environmental issues surrounding conventional animal husbandry by developing an industrial cultured meat production process with integrated 3D printing technology. It aims to develop a customised process to manufacture protein without animal slaughter.

MeaTech was also among the companies that went public last year in 2021.

ORGANOVO HOLDING INC. (NASDAQ: ONVO), MARKET CAPITALIZATION: $32.82M

San Diego-based Organovo is at the 12th position in the list of the world's largest 3D printing company with a market cap of $76.65 million. Known to transform the future of regenerative medicine with its 3D bioprinting technology, the company has partnered with several pharmaceuticals, medical centers and develops 3D human tissue models that could be used for different medical purposes such as biological research, predictive preclinical testing of drug compounds, therapeutic implants and even to treat damaged or degenerating tissues and organs.

VOXELJET AG ADR (NASDAQ: VJET), MARKET CAPITALIZATION: $30.57M

The next on this list of the world's largest 3D printing companies with a market cap of $96.59 million is Voxeljet. A manufacturer of 3D printing systems for industrial applications, Voxeljet is known for its large-format production and a chemical 3D printing process. The company caters to industries that range from automotive, aerospace to architecture and design.

FINAL THOUGHTS

The list of 13 of the largest and the best 3D printing companies around the world also offer a great representation of the entire 3D printing ecosystem. This list has some of the biggest 3D printer manufacturers, 3D printing service providers, software manufacturers and also one of the top medical/healthcare 3D printing company.

ENVIRONMENTAL ISSUES AND TRENDS

To assess the environmental friendliness of the 3DP, indicators such as energy consumption, carbon emissions, use and production of toxic substances are selected. One avenue for future research is using the Life Cycle Assessment (LCA) to assess the environmental impact of 3DPs. LCA is one of the most widely used environmental assessment tools in buildings.

As an assessment method, LCA involves the collection, processing and analysis of vast amounts of data. It takes a lot of time and effort. Therefore, information software tools such as BIM are required to support LCA. BIM is a construction management method based on the life cycle with a wide range of stages, including design, planning and operation, energy consumption and emission, etc. Relevant research is currently underway on a building environmental impact assessment method called BIM-LCA, and 3DP environmental impact assessment has shown that it can improve efficiency and accuracy.

LEGISLATIVE ISSUES AND TRENDS

Despite its potential benefits, 3DP has not yet reached its full potential in the construction industry and is not a technology capable of completely replacing traditional construction methods.

In terms of intellectual property, there are laws and regulations that protect new inventions and inventors. One area of future research will be to establish principles for the protection of intellectual property for 3D models.

BUILDING STANDARDS

The application of 3DP in construction requires the creation of standardized building codes, which currently do not exist. There are many materials, types of equipment and processes, but there are no clear requirements for materials, processes, calibration, testing and document format standards. In the future, it will be necessary to set standards for materials, manufacturing processes and designs.

With the development of 3DP, the compatibility and accuracy of BIM software needs to be improved.

SOME EXAMPLES OF THE USE OF 3D PRINTING IN CONSTRUCTION

NEW DEVELOPMENTS

Company Diamond Age has created a technology that will speed up the construction of residential buildings from 9 months to 30 days using 3D printing.

Diamond Age believes that there is only one solution to this problem - the automation of construction projects and the abandonment of most of the staff.

The company relies on robotic installations and efficient 3D printing. These units include a set of 26 different attachments for construction robots to assist with transporting building materials and laying foundations. An effective 3D printing is achieved through "portal-based" printers – large-sized units quickly print the internal and external walls of the future building.

1. CHINA BUILDS 3D-PRINTED SWING BRIDGE

Recently, China has come out on top in the world in terms of innovation. For example, the Bay of Wisdom in Shanghai is built on the site of a former wool textile factory and is home to over 300 international companies involved in 3D printing, smart micromanufacturing, virtual reality (VR), augmented reality (AR) and artificial intelligence. (AI) robotics projects. It is supposed to be the only 3D printing museum in the world.

Several innovative 3D printing projects have taken place in the bay in recent years. One of them is a 3D printed sliding bridge.

The sliding bridge weighs only 850 kg, is nine meters long, 1.5 meters wide and 1.1 meters high. The structure was installed over a small pond in Wisdom Bay. The bridge can accommodate up to 20 people at a time.

The bridge is made up of 36 triangular panels, each was 3D printed with a different design, reminiscent of outward waves. Printed within three days, the panels are made from carbonate polyester composite material, which is considered environmentally friendly.

The bridge is divided into nine segments. The retractable element of the bridge is controlled via Bluetooth: the structure unfolds through the water in a spiral shape in less than one minute. The bridge is also equipped with an automatic gravity warning system to prevent overloading.

Economic effectivity: A few years ago, one of the Chinese companies conducted an experiment: 10 houses were printed there in a day. Each cost only $4,800. That's just the example of China around the world is not in a hurry to follow. High technologies are preferred to be used for the manufacture of houses of complex structures.

2. UK

The UK intends to accelerate the construction of the High Speed 2 (HS2) railway network with the help of 3D printing of reinforced concrete structures at the site of the robot. A 3D printing method in which concrete is reinforced with graphene (dispersed reinforcement). It will also significantly reduce the carbon footprint of construction.

The reason for this decision is the advantages of the new technology.

The technology, dubbed "Printfrastructure", is developed by London-based tunneling contractor HS2 Ltd - SCS JV (Skanska Costain STRABAG Joint Venture). It will help build a high-speed rail line in the UK linking London, Birmingham, Manchester and Leeds.

Some advantages of 3D printing:

The use of remote controlled robots will allow SCS JV to 3D print structures on site, eliminating the need to transport them on the road. 3D printing technology makes it possible to build structures in a limited space, which means that complex and expensive logistics operations will no longer be required.

Since the work is carried out on site by 3D printing robots, there is also no need to suspend work to ensure the safety of people. All this will speed up construction time and cause less inconvenience to the local population.

Reinforced concrete structures built using a reinforcing internal grid that reduces the amount of concrete needed. It also produces less waste.

Finally, the concrete used for the 3D printing process is reinforced with graphene, the strongest material on the planet. Microscopic filaments of graphene, just a few atoms thick, replace steel rods, making it easier to build structures while at the same time giving them greater strength and a smaller carbon footprint. The graphene innovation was developed by SCS JV partner in Worcestershire, ChangeMaker 3D.

From an environmental point of view, this process will reduce carbon emissions from railway construction by up to 50%.

3. USA

In recent years, 3D printing in housing construction has become a mainstream construction technique. And Icon is positioning itself as a major player in this area. Shortly after unveiling plans to print a simulated Mars base with NASA and the Bjarke Ingels Group, the company completed 3D printed houses in East Austin [13].

To create the ground floor, Icon used its Vulcan 3D printer, which extrudes a proprietary cement-like mixture from a nozzle in layers. However, the top floor was built by builders from wood. This contrasts with the Kamp C experimental house, which was completely 3D printed in Europe.

PIC. 5: GENERAL VIEW OF HOUSES, GROUND FLOOR CREATED WITH 3DP IN THE USA.

The project was created in collaboration with 3Strands and Den Property Group, as well as Logan Architecture. While the houses are the first 3D printed homes to hit the US housing market, they almost certainly won't be the last. The firm has already unveiled its vision for the future of 3D printed housing in collaboration with Lake | Flato Architects.

U.S. Army will be one of the biggest costumer of 3D-printed structure [14]. For example, barracks will be largest in the West. At the next picture is example of barrack for 72 soldiers.

PIC. 6: THE PROJECT WILL CONSIST OF THREE BARRACKS, EACH OF WHICH WILL MEASURE OVER 5,700 SQ FT (ROUGHLY 530 SQ M) ,LOGAN ARCHITECTURE

PRINTED IN UNDER A DAY, THE B-HUT

The B-Hut is the largest 3D printed concrete building in the US by and only took 21 hours to manufacture at the Construction Engineering Research Laboratory

(CERL) of The US Army Engineer Research and Development Center (ERDC) in Champaign, Illinois.

The structure is the latest to be 3D printed as part of the Automated Construction of Expeditionary Structures (ACES) project. CERL has previously 3D printed a smaller 512 square foot B-Hut, but this latest building is the latest to be manufactured using an in-house ACES-3 3D printer that was unveiled by CERL in September 2017.

The third generation concrete 3D printer was developed by ACES together NASA's Marshall Space Flight Center, Kennedy Space Center, and Caterpillar, Inc. It is capable of 3D printing custom-designed expeditionary structures on-demand, in the field, using concrete sourced from locally available materials. However, as with other 3D printed buildings, the roof and other horizontal surfaces were not 3D printed.

"It could be used to make refugee housing. It could be used to print disaster relief housing." US Army ERDC mechanical engineer Megan Kreiger explainedto FOX Illinois. "Its applications have barely been touched because we are on the cusp of this developing technology."

PIC. 7: 3D PRINTING THE NEW B-HUT. PHOTO BY ERDC.

4. RUSSIA

In Russia began to build houses by 3D printers. So in 2022, several regions of Russia plan to print houses using 3D printers. “Since 2014, we have sold more than 220 printers to 15 countries around the world,” Alexander Maslov, CEO of AMT, told RG. “There are houses printed on our printers in Yaroslavl, Ufa, Yekaterinburg and others. There are buyers from Copenhagen too.

Most printers, according to Maslov, are now buying the southern regions of Russia. The materials used for printing work worse in the conditions of the north. The AMT company, a resident of Skolkovo, does not build, but for the sake of testing developments, it began to print houses at its site near Yaroslavl. They want to build 12 buildings ranging from 60 to 180 square meters and up to three floors high.

Construction speed: 100 square meters in two days, Andrey Rudenko, CEO of Totalkustom, said. Stand the foundation in the usual way and build walls with the help of 3D printing. At the same time, communications are being laid. Printed walls cost 30 percent less, and the entire building costs 8-12 percent less. With mass construction, the cost per square meter of the building is $300.

3D PRINTING IN ISRAEL

GREEN 3D PRINTING: AN ORGANIC AT ARCHITECTURE [15]

Between 23 and 30 June 2022, Jerusalem Design Week welcomed over 40,000 design enthusiasts to the Hansen House Center for Design, Media and Technology, for the showcase of an eclectic mix of exhibitions, installations and projects from over 150 Israeli and international designers. Work by invited designers centered around this year’s theme ‘For Now’, exploring both the ephemerality of design and the design of ephemerality, and examining ways in which time can be harnessed to bring about a positive effect in periods of uncertainty.

Among the participating exhibits was the ‘To Grow a Building’ project, which examines possibilities of an organic architecture in the face of a global ecological crisis. With the use of industrial and non-local resources only increasing, ‘To Grow a Building’ proposes architecture that uses raw, natural materials such as local soil and roots as structural elements to replace unsustainable buildings made of concrete and steel. **The project** presents a new approach of integrating flora into the architectural design process, by developing a novel material for 3D printing through which seeding is an inseparable part of the fabrication process.

PIC. 8: EXAMPLE OF PRINTING PROCESS AND GREEN LIFE RESULTS.

PIC. 9: EXAMPLES OF PROCESS MATERIAL PREPARATION FOR 3D PRINTING AND POSSIBILITIES OF AN ORGANIC ARCHITECTURE

4

3D STARTUPS IN ISRAEL

There are about 40 3D-Printing startups in Israel. For example, here is a list of some of exciting ones.

Provider (2018) of 3D-printed meat

Provider of 3D-printed meat. It is a meat processing company using 3D technology that delivers animal-free meat with the same appearance, texture & flavor by using natural and sustainable ingredients. It provides 3D meat digital modeling, food formulations & food printing technology to deliver a new category of complex-matrix meat. Its products are free of cholesterol and healthy.

XJet (2005)

XJet is a provider of metal and ceramic additive manufacturing technologies. The company has developed metal Jetting systems for additive manufacturing based on NanoParticle Jetting (NPJ) technology which is like an ink-jet technology for printing metals. The product portfolio of the company includes Xjet Carmel 1400 (features a 1,400 square cm build tray) and Xjet Carmel 700 (features a 700 square cm build tray).

Castor (2017)

Provider of cloud-based 3D printing management software. It is an additive manufacturing company that develops 3D printing software for optimizing the manufacturing process. It runs an analysis to determine the 3D printability of end-use parts, estimate 3D printing costs and supplies a financial analysis. It caters to multiple industries, including the automotive, aerospace, medical devices, logistics and transportation industry.

3DShook (2014)

3DShook provides gallery 3D printable tested designs designed by professionals. They introduced unlimited subscription plans to access the 3D models. They also sell printers of major brands and provide apps also.

PrintCB (2016) [16]

Provider of advanced copper materials for copper printing and coating. Its product portfolio includes copper nanotubes, functional copper coatings, and conductive copper solutions for plastics, aluminium, ceramics, and glass surfaces. It has applications in printed electronics, automotive, power electronics, Lighting, and energy sectors.

Copprint (2016)

Provider of copper-based conductive nano inks. It features rapid sintering by standard heating methods and more bulk conductivity. Its other benefits offered by this method include substrate freedom as it's not negatively impacted by heating, robust conductive elements, and no environmental impacts. It has applications in RFIDs printing on paper, touch panel bezel contacts, printed antennas, printed PCBs, heaters, defoggers, fabrics, 3D printing of conductive patterns, batteries, and manufacturing of other printed electronics.

Assembrix (2014)

Assembrix offers SaaS-based solutions to businesses in the additive manufacturing or 3-D printing sector. It helps the 3-D printing process by improving printing speed, quality and reducing its cost by utilizing algorithms and big data. The platform offers automatic orientation which orients parts to their optimal position to reduce material usage and time for printing.

Creative IC3D (2015)

Creative IC3D is developing technology to implement three-dimensional printing in manufacturing circuit boards. They are integrating number technologies with multi-disciplinary chemistry such as Inkjet, Nano technology to develop prototype circuit boards through 3D Printing. They claim it will reduce manufacturing time of PCBs to hours from weeks. They completed writing part of developing plan as of July, 2016.

Printsyst (2017)

Printsyst has developed a cloud-based 3D printing assisting platform. The software platform is based on the company's patented AI algorithm. As of July 2017, the company's portfolio consists of PrintSYSt PO and PrintSYSt Hub.

Kazzata (2013)

Kazzata has developed platform for manufacturers to cut short the supply chain for spare parts distribution. In their platform manufacturers can store and distribute CAD files of spare parts on request basis. It will cut short the supply chain and eliminate the need of mass production and storage of spare parts. These CAD files can be used to get a 3D print of the spare parts.

Largix

Largix has created the first 3D printer able to produce large industrial storage tanks and other items from common and recycled polymers (Fig. 10).

Storing and transporting hazardous liquids is a dangerous business. The secure, 13-foot-high storage tanks currently produced by CGK Group, based in Bruges, Belgium, are all hand-made – an expensive and labor-intensive process.

Now, using the world's largest robotic 3D printing platform created by Largix, an Israeli startup, CGK expects to slash the cost of creating the tanks.

"This will be a gamechanger for us," says Geert Denutte, the founder of CGK. "Nobody else is doing such technology. We estimate it will save us up to 50 percent in costs."

PIC. 10: LARGIX'S ROBOTIC PRODUCTION PLATFORM CAN PRODUCE 3D-PRINTED INDUSTRIAL ITEMS FOR INDUSTRY INCLUDING ROOM-SIZED STORAGE TANKS FOR CHEMICALS (LARGIX)

In addition, because the technology is automated, it can work "25 hours a day," says Denutte, dramatically cutting the time required to make the tanks.

Until now, 3D printers have been unable to produce large industrial products at industrial speeds and costs. Largix's Cold 3D Printing technology will use smart sensors with real-time data and machine learning to produce large objects with the required bonding and welding strengths. It is the first system that makes 3D printing possible for real industrial production, using polypropylene and polyethylene – common thermoplastic polymers that nobody else is capable of printing.

“Largix is the only company that can print in these materials because of their technology,” says Charle. “Nowadays, we produce our made-to-measure vessels out of semi-finished products. This needs a lot of manual labor next to a significant amount of scrap material. The platform will reduce our dependency on labor, increase our productivity and, next to the substantial labor-cost savings, the Largix Robotic Production Platform brings new opportunities in terms of shapes and new materials.”

“3D printing technologies are mainly capable of making models and prototypes from polymers,” says Ronen Orr, co-founder of the company with Amir Sheelo. “Both of us have more than 20 years’ background in traditional industries, making traditional products. We decided to develop a 3D printing technology that would be able to industrially produce real products reinventing traditional, labor-intensive, design and production of custom-made products made of polymers and composite materials, across diversified industries.”

Conclusion

In recent times, 3D concrete printing (3DCP) is considered an emerging high-tech development in construction technology. However, it is too early to say whether 3DPC can fully replace current concrete construction methods such as cast-in-place and precast parts. At this moment it is necessary to find the complexity in the current construction methods and justify whether 3D printing can be used to remove this complexity. A current limitation and research need of 3DCP in the building and construction (B&C) industry lies in automatic horizontal and vertical reinforcement. It can contribute to the automation of B&C by 3DCP, which can eliminate shapes and produce complex 3D geometries with minimum time and human interaction and high geometric accuracy. It is mandatory that the characterization of the hardened characteristics is also carried out according to standard test procedures to enable appropriate engineering planning.

Finally, before 3D printing is accepted as a new construction technology by B&C authorities, standards for materials, specification, fabrication and structural design are required. These standards and their appropriate application in design and construction must ensure that appropriate levels of reliability are achieved. In the simplest form, this can be achieved by bringing additional considerations and requirements to the attention of building designers, similar to prefabricated construction, to which a separate chapter is dedicated in Eurocode 2 for concrete buildings.

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