A BRIEF OVERVIEW OF THE USE OF ADDITIVE MANUFACTURING OF CONCREATE MATERIALS IN CONSTRUCTION

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Highlights
- 3D printing is becoming more and more popular in construction industry up to architectural design to building performance.
- 3D printing brings a lot of advantages in the construction industry, for instance: low labour costs, less waste, and high efficiency.
- Material design for 3D printing is important element for efficiency of this technology.
- 3D printing requires development and optimization for further construction application.

Abstract
Currently, additive technology is becoming increasingly popular in different areas, including its applications in construction industry. The main aim of the chapter is to show the selected applications of 3D printing technology in the construction industry and the usage of this technology on distinct stages of a construction project, from architectural design to performance of residential buildings and other civil engineering constructions. The chapter is based on a critical analysis of the literature sources, as well as the authors' experiences. The data collected are supported by selected case studies from five projects. The main findings show that 3D printing brings a lot of advantages in the construction industry, for instance: low labour costs, less waste, and high efficiency, but it still requires development and optimization.

Keywords
construction industry; additives technology; 3D printing; geopolymer.

Introduction
Additive manufacturing (also popularly called 3D printing) is a production process during which a solid 3D object is created from a numerical model by developing layers. Nowadays, this technology is gaining popularity in different industries, for example, automotive, medicine, education, etc. [1,2] Nowadays, interest in this technology is also emerging from the construction industry [3,4].

Additive manufacturing could bring many benefits to the construction industry. It could offer novel possibilities in this sector, including improving geometrical flexibility of buildings, minimalization the cost of labour, enhancement safety and improvement efficiency, as well as possibility to work in new, harsh environments and also better sustainability of the constructions [5,6]. From an architectural point of view, flexibility is a very important feature. It allows for better creativity and the design of more complex forms and shapes, including curvilinear ones. It helps with more sophisticated and aesthetic design, fulfilling the mechanical requirements. Additionally, optimized topologies allow for cost reduction because of material efficiency [7,8]. Additive manufacturing technologies also make it easier to produce individually designed elements for residential houses as well as public buildings, at the same price as the 'standard' one. It is important not only because of aesthetic requirements, but it could also significantly influence functionality, including the specific needs of people with disabilities [9,10].

Other advantages are reduction of labour costs as well as improvement of efficiency and safety of the building process. The additive manufacturing technologies minimize the manpower involved in the production process through automated manufacturing [8,11]. These technologies also have high cost-effectiveness and present high precision of execution of building elements. In the same time, they have a low-unit on-demand manufacturing compared to traditional ones [4,11]. The main reason is the reduction of additional elements, including forms, shuttering and other elements of formwork [7]. Another important element of additive manufacturing technologies is the possibility of construction in harsh environments such as subarctic climate or in-space applications; some tests have been provided for shelters on the Moon [12–14]. Finally, the sustainability of this technology is an essential element [4,11]. Effectively reduces waste, including formwork construction wastage. It means that a low amount of material can be applied for different operations, such as moulding and casting. Using these technologies, the environmental impact is limited and the carbon footprint is reduced (by minimizing inefficiencies during the building process, transportation, etc.) [6,7,15]. Regrettably, the full exploitation of additive technologies in the construction industry is currently constrained [4,11]. One of the most critical challenges of these technologies is the availability of suitable materials, especially dedicated to the large-format 3D printer [15–17]. Another challenge is related to post-processing procedures, which on a large scale are difficult to apply on a practical basis [18]. The article presents the application of additive technologies in the construction industry, including applied technologies, materials, and case studies of the practical applications. Finally, it presents the state-of-art in this new, promising area.

The use of 3D printing in building design
3D printing technology, apart from being used in construction, is also very often used in architecture, for example to create spatial models and mock-ups. It is a method that increases architects' creativity and competitive advantage by quickly creating printed models of houses and even entire estates [19]. Thanks to this technology, it is possible to develop various illustrative versions and spatial variants. The benefits it brings are enormous [19,20]. The 3D printing very faithfully reflects the technical design. The models are more durable and made in much shorter time than those obtained with the traditional method. In addition to conventional and cubature buildings, 3D models are used to design other engineering constructions, for example, bridges. Due to this, it is possible to verify the accuracy and eliminate potential errors in the design stage [21,22]. The application of 3D printing technologies in this case allows for, i.e. [19]:

- Transformation of three-dimensional digital sketches and CAD models into spatial models;
- Visualization and communication of design ideas to others;
- Study and experiment with various complex shapes;
- Reuse of projects and their components;
- More time dedicated to coming up with different project concepts;
- Doing something else while the 3D printer produces a model that is more illustrative than the computer visualizations currently being used.

The benefits of 3D printing technology for architects are invaluable. They can, for example, display faithful architectural reconstructions. It is already certain that 3D printers are gaining more and more importance as

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a tool of architects and the architectural and related industries [23,24]. Printers provide the possibility of presenting alternatives of various design versions on a physical model, the use of precise working mock-ups, or multiple replications of the model for each of the consultation participants or the project team [23,25].

The typical architectural design using additive manufacturing has several steps [23,26]. Firstly, the virtual model built in a CAD program is not suitable for printing. It is related to the recording format and the modelling method. Despite the fact that the formats from AutoCAD or 3ds Max are relatively easy to export and save in a format that allows 3D printing, the solid may be corrupted during the export and it will be necessary to repair it. The flaws of the created models are all kinds of imperfections, especially leaks and overlapping lumps. Next, a digitally built model may be interpreted by the software as unprintable. Finally, manufacturers of software for 3D printers have created solutions to automate the repair process and check models for printing [23,25].

Printing technology for civil engineering constructions

3D printing technologies are finding more and more supporters in construction [27,28]. They use not only conventional construction materials, but there are also developed non-standard materials for construction occurring locally, e.g., sand in the Sahara Desert or regolith dust on the Moon.

Additionally, the designed solutions allow the printing of sewage pipes and electrical cables [19]. When it comes to efficiency, it is estimated that building with 3D printing technology gives us 35-50% shorter construction time, 30-50% lower costs, and fewer accidents during construction [29]. Selected benefits/advantages and disadvantages of using 3D printing technology in construction are presented in Table 1.

Table 1. Selected advantages and disadvantages of using 3D printing technology in construction. *Source: [7,28]*

Benefits of using 3D printing in construction	**Disadvantages of using 3D printing in construction**
Increased safety on the construction site	High financial outlays for construction equipment
Reduction of waste materials	Low bonding material yield
High accuracy of printed elements	The need to constantly control the quality of the printed object
Free-form making and easy modification	Insufficient conditions for the completion of the building structure as a whole
Shorter the construction completion time	The correct implementation of the additive printing technique strictly depends on the raw materials
Lower investment costs-relatively low technology costs	
More accurate and easier construction logistics	

The disadvantages associated with the implementation of additive technology also include issues related to the loss of many jobs and the need to employ highly qualified workers [30,31].

Three main technologies are used to print entire buildings and larger structures as well as large elements: CC (Contour Crafting), Concrete printing and D-Shape [32,33]. It should be remembered that the use of additive technology in building industry is not only the creation of structures but also the production of other building elements and more. Thanks to this technology, we can create garden accessories, bathtubs, washbasins, bridges and footbridges and many other elements used in everyday life [34,35]. An example of a building elements printed in 3D technology and the process of manufacturing is shown in Figure 1.

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(a) (b)

Figure 1. An application of 3D printing in the building industry: (a) building elements printed with 3D technology; (b) manufacturing process. *Source: Own.*

Technological solutions, construction of printers

The most important element of additive manufacturing is an innovative approach to the production process. It is a little bit different for various types of 3D printing processes, but significantly different from the traditional manufacturing process [8,11]. In the case of 3D printing, the first stage is to design a 3D numerical model. This is usually done by using CAD software, but this is not the only possibility. Currently increasingly the model might be designed with 3D scanning, created by the designer or based on another existing design. Later, the numerical model is transformed into the standard tessellation language (STL) format. STL is the most recognizable format for 3D printers. The subsequent step is connected with uploading the file to the computer that controls the 3D printer. Some changes could be implemented in the object at this stage by setting up the device, for example, size. When working, the 3D printer should be checked regularly. Supervision of the process is needed in case of errors. When the process is completed, the printed object is taken from the machine (or in the case of large-scale devices in the construction industry, the 3D printer is removed from the object). The final step is post-processing. This process could involve different technical operations, such as brushing off the object from remaining powder, support removal, painting, polishing or curing [11,36]. The manufacturing process could be different for each construction, because a variety of techniques can be applicable in additive manufacturing. The American Society for Testing and Materials (ASTM) divided 3D printing technologies into seven categories [37]:

- Material Extrusion, together with Fused Filament Fabrication (FFF) and Fused Deposition Modelling (FDM);
- Sheet Lamination;
- Material Jetting;
- Vat Photopolymerization, incorporating Stereolithography (SLA), Continuous Liquid Interface Production (CLIP), and Digital Light Processing (DLP);
- Powder Bed Fusion, together with Selective Laser Sintering (SLS), Multi Jet Fusion (MJF), and Direct Metal Laser Sintering (DMLS);
- Binder Jetting;
- Directed Energy Deposition.

In the construction industry, there are the most popular: material extrusion and powder bed fusion. The most popular seems to be material extrusion. Nowadays, it is the most applied technique for large-scale objects. Extrusion technology is characterized by a layer-by-layer structure. It is an effect the material extrusion through the nozzle mounted on a gantry to print. It also allows the construction to be printed on-site [4,11]. The application of powder bed fusion gained popularity for the smallest elements that required more precision and should have a high aesthetic value [38,39].

Materials used to print buildings

The possibility of quick construction of residential buildings using 3D printing techniques allows for reduced production costs and creates hope for people who, due to the high prices of traditional houses and low wages, cannot afford to buy their own apartments. This tendency applies to all European countries where housing is becoming too expensive for lower-income groups [27,28]. The use of correct materials is not without significance in 3D printing technology [40]. On the one hand, it should use cheap materials, since the aim is to make it possible to obtain cheaper buildings, and on the other hand, these materials should have specific properties. Materials used for 3D printing should be able to cure quickly, should be able to maintain a spatial structure (not spill), be able to be extruded, etc. Of course, one of such materials is conventional concrete based on Portland cement, but it should be remembered that not all elements of houses or other objects can be printed from concrete, and not everywhere it is possible [40].

In the last few years, many ideas have arisen related to the use of 3D printing technology on the Moon, using the materials that can be found there. These plans assume the use of regolithic dust and sulfur concrete. These materials can be obtained on-site and there is no need to transport them. These are very advanced plans that are already implemented and tested to some extent. The vision of creating objects on the Moon in 3D printing technology is no longer as futuristic as it seemed not that long ago. Printer designs assume the installation of photovoltaic panels on printers so that the entire 3D printing system is powered by solar energy [41,42]. Currently, one of the very interesting materials for additive technology in the building industry are geopolymers. Geopolymers are materials known as inorganic, amorphous, synthetic, and aluminum silicates with specific compositions and properties. Comparison of geopolymers with other building materials is shown in Figure 2 [43].

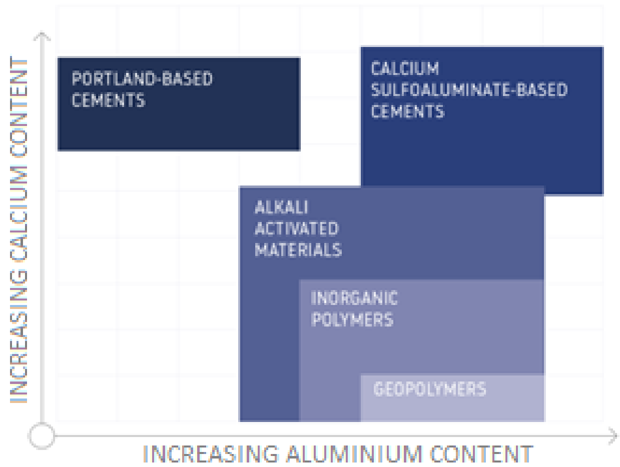

Figure 2. Classification of binders and geopolymers. *Source: [43]*

Investigation on geopolymers is performed primarily to reduce Portland cement application, because of the needs of reduction the influence of the building materials on environment. Related research objective is increasing the usage geopolymers in the construction industry and applicability this material in large scale. The provided analysis show that this material can be much more effective that traditional concrete, including decreased nearly 50% energy demand and almost 32% total costs [44]. Moreover, this material gives a reasonable promise of limitation in CO_2 emissions and reduction in global warming [45,46].

Geopolymers are, most often, hard, and mechanically resistant solids that resemble natural stone or concrete. All types of geopolymers are characterized by very high refractoriness. Most methods of geopolymer synthesis come down to one process: comminated, dried pozzolanic material (metakaolin or fly ash) is blended with an aqueous solution of a suitable silicate (e.g., sodium or potassium silicate) joined with a strong base - usually concentrated sodium or potassium hydroxide. The paste obtained has a similar behaviour to cement: it solidifies to the required elements in a few hours [47,48]. This process was traditionally applied in casting technologies. Today, there are some experiments to apply it to 3D printing process. One of the first trials was conducted in Irkuts (Russia). The successful tests of the use of géocrete (geopolymer concrete) in printing structures were carried out on a mobile 3D printer from Apis Cor [49]. This system was developed by Russian-Italian company RENCA. This company has developed and assessed various material compositions based on a geopolymer binder. Tests have shown the high performance of geopolymers, including a very good consistency suitable for extrusion technology [49]. Moreover, the company declares the obtained formula is the most relevant for the additive technology, because of proper setting time, high thixotropy and relevant fluidity of the geopolymer paste. It should be noted that the products achieved are characterized by high aesthetic values and excellent mechanical strength (compressive strength - 100 MPa) [49,50]. Additional advantage for construction industry form the application geopolymers in 3D printing technology can be short construction time and environmental benefits, including usage of industrial by-products as a raw materials [14].

However, 3D printing for geopolymer materials is a challenging task and is connected and numerous trials and failures (Figure 3a) make it is a promising alternative for concreate constructions. The investigation also show the possibility to join this two materials in so called hybrid solutions (Figure 3b) [15,51].

(a) (b)

Figure 3. Trials of 3D printing: (a) 100% geopolymer based on fly ash - too high viscosity; (b) Hybrid solution – geopolymer and concreate. *Source: Own.*

For the further development of 3D printing technology, new materials with programmable properties are necessary. It could be achieved with different additives, for example, gypsum waste that helps with regulation the setting time [52]. Currently, construction solutions are available that allow 3D printing for the construction industry with the following materials [43]:

- Various types of concrete and hydraulic binders;
- Geopolymers and alkaline activated materials;
- Plastics, rubber;
- Sands and regolith, clays;
- Salt, waste from coffee, tea, and wine production.

<u>Examples of printed objects around the world</u>

The application of additive manufacturing in the construction industry is connected to the search for opportunities to improve efficiency and profitability in this area. One of the most exploited technologies in recent years in the area of the building industry is Building Information Modeling (BIM). BIM technologies use modern software to improve the efficiency of management in the whole construction project at all stages – starting preconstruction, trough the on-site coordination, up to implementation the changes during the project [53,54]. Nevertheless, BIM changes the management of the construction process, it does not change the process itself. The traditional building methods have been similar for decades. Meanwhile, additive manufacturing introduced changes in construction technology as such. It has the potential to improve the efficiency and profitability of the building process, make this process more sustainable, and achieve a positive environmental impact [8,54]. However, as it exists today, additive technology has many limitations, for example size of the structure, the material used, the requirements for skilled labor, as well as industry reluctance [8,55].

Recently, 3D Concrete Printing (3DCP), realized by extrusion method become very popular as an object of research and development works in the construction industry [55,56]. It is considered an emerging technology that has a potential to revolutionize the construction industry [57,58]. In the construction industry, the use of 3D printing is constantly growing. The new architectural tool, which is the use of this technology, gives unlimited possibilities in the selection of form and technique. Today, 3D printing is used for not only residential houses,

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but also many other urban elements. This technology on an architectural scale is becoming more and more popular, offering many benefits [29,56,59]. One of the spectacular architectural structures is the longest 3D printed bridge in the world.

Case study of bridge in Shanghai

The concreate bridge in Shanghai in one of the first of this type constructions made in the world (Figure 4).

Figure 4. 3D printed bridge in Shanghai. *Source: [60].*

It was made using extrusion technology (contour crafting) with the robotic arm for feeding the material. The basis for the contour crafting method is the quick application of successive, thin layers of materials, in this case concrete, one on top of the other according to a computer pattern. In case of residential housed this technology leaving space for windows and doors in the walls [61,62]. In case of the analyzed bridge this technology allows to obtain aesthetic shape coherent with architectural vision made by Professor Xu Weiguo from the Tsinghua University (School of Architecture) - Zoina Land Joint Research Center for Digital Architecture [62,63].

The bridge project was inspired by the ancient Anji Bridge in Zhaoxian, China. The object is composed of 44 hollowed-out 3D printed concrete elements and is the 26.3-meter-long bridge. In addition, the handrails are made from 68 elements. The bridge was created from some components. Each of them has been performed in additive manufacturing technology. As a base material, concreate reinforced with polyethylene fiber was used [64]. The application of composite material allows joining the structural performance of conventional materials with increasing level of material ductility by fiber addition. The bridge was printed by two automatic arms in 450 hours. The streamlined process is estimated to have resulted in savings of 33% production costs compared to the more conventional construction process [65]. The use of the new technology can cause a change in construction projects due to its characteristic of automation and robotic work [63]. It also has the potential to replace labor with machinery on a construction site [63].

Dubai Municipality - case study of an administrative building

The 3DCP technology also finds application in residential and public buildings. One of the most advanced projects in this area took place in Dubai (Figure 5). The two-storage administrative building for Dubai Municipality was design and performed with usage nearly fully automated construction process with significant reducing formwork works and minimalizing human resources [64,65].

The main contractor for this project was the previously mentioned Apis Cor that cooperates with the RENCA company in Irkuts, Russia, in testing new materials, geopolymers for 3D printing. Despite the environmental conditions in Russia, the climate in Dubai is more favorable for the construction industry, including 3D printing technology, due to the more suitable temperatures for this process. The additive manufacturing technology was applied to the manufacturing of wall structures. They were 9.5 m tall and covered an area of 640 m^2 [66]. Today, it is still one of the largest 3D printed structures [66]. The material used for the production of the two-story public building was a gypsum-based mix developed by Apis Cor. It is also worth to noticing that structural calculation and analysis covered all areas required for the building: seismic actions, floor masses, accidental torsion effects,

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etc. The prototype solution was tested according to ASTM norms, including mechanical properties (compressive strength and three-point flexural test for material and elements), absorption and durability test. Due to the lack of separate building regulations for building in 3D printing technology, tests corresponding to conventional building materials were applied [67,68].

Figure 5. 3D printed administrative building for Dubai Municipality. *Source: [64].*

Case study of 3D printing applications in the construction industry

The other application additive manufacturing in building industry that was connected with many benefits is production ten small, full-size prefabricated houses by Shanghai-based Winsun in 2013. The main benefit of the usage of this technology was the time for production - ten whole houses were 3D printed in one day. The additional benefit was associated with the price of this project only, $ 4,800 for one house with an area of 200 m^2 [69]. Each house was 6 meters high and more than 12 meters wide [69]. This cost-efficiency was possible mainly thanks to reducing employment and saving production costs [69]. However, it is worth noticing that these houses were not completely printed on-site. They included mainly pre-fabricated elements in the company and next shipped to the construction site. On the site, there were installed on a slab foundation and there reinforced by steel rods [69]. Moreover, some construction elements, such as roofs, doors, and windows, were not made in additive manufacturing technology. The used 3D printing technology was focused mainly on the walls. These elements were made in the technology that remained the hollow bridge that ensures a more lightweight construction and increasing isolation properties. The internal spaces were reinforced by the diagonal zigzag system to obtain the proper strength of the construction elements [69]. At the same time, however, it provides enough space for plumbing and electrical installations. The material used for this project was the composition designed for 3D printing process. It was also registered as a trademark. The composite consists of concrete, cement, gypsum, glass fiber reinforcement, etc. The important property of this mixture is the high early strength of the material and short time of curing - within a few days. Important feature of the designed material is also sustainability – about half ingredients by mass comes from recycled construction waste [69].

The similar material (concrete, gypsum glass fiber etc.) a few years later realized also more ambitious construction, the first 3D printed office building in the world. This building was dedicated to the United Arab Emirates National Committee as the headquarters of the Dubai Future Foundation (DFF) – Figure 6 [70,71].

The whole structure is 250 m^2. Construction technology was similar to previous project: not all elements were produced on site. It is estimated that about half of them were produced at the factory, shipped and assembled on site. This whole process involves only 18 workers (printer operator, assembly workers, mechanics, and electricians' staff). This number was significantly lower than in the case of traditional construction works. Moreover, the new technology allows considerably shortened the construction time – the whole project was finished within only 17 days. Both of these elements help to reduce the investment cost of about $ 140,000 [70,71]. It is worth to noting that estimation shows huge reduction of manufacturing time (50 – 70%), reduction of labor cost (50 – 80%), and minimalization of construction waste (30 – 60%) [71].

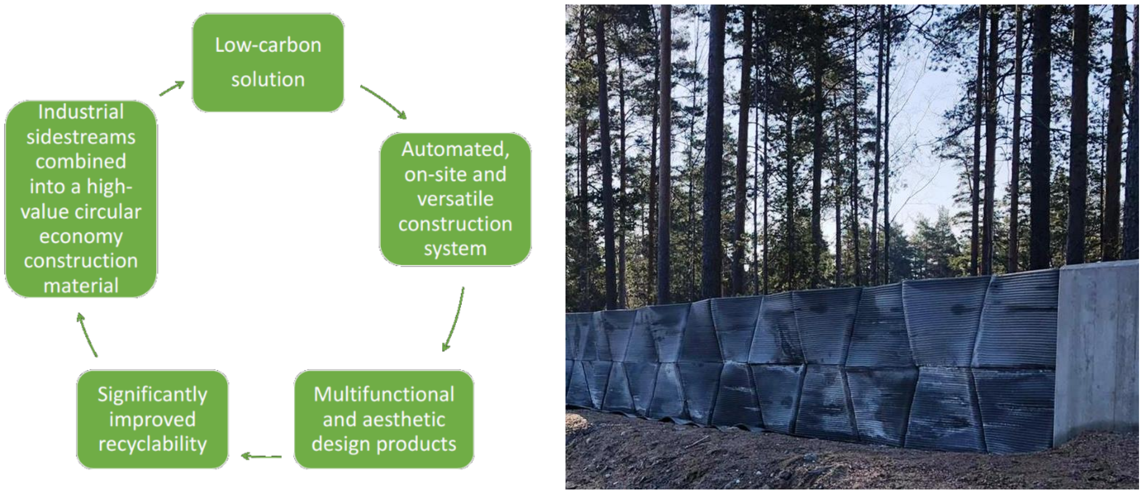
Figure 6. 3D printed office building in Dubai. *Source: [70].*

Case study of small 3D printed urban architecture in Lapperanta

The other example of using 3D printing technology for construction purpose is the project "Urban infra revolution: Circular economy materials and the development of novel methods to produce recyclable and functional urban construction products", co-financed by the European Regional Development Fund through Urban Innovative Actions (UIA) [72,73]. The project was implemented between 2017 and 2020 by the consortium, which involves: municipal - city of Lappeentanta, Finland (lider), four small-medium enterprises (SME), five private enterprises (large), two universities, and Region Development Company. The total cost of the project was: EUR 4 336 568.40 [11,72,73]. This project implemented new solutions to reduce CO_2 emissions in the development of urban construction. It includes three innovative components: material, technology, and product. The first innovation was new materials that were designed to replace concrete in urban architecture. They are based on side streams from local industry, such as ashes, green liquor dregs, mine tailings, construction and demolition waste. The additional material requirements were coherence with additive manufacturing technology (3D printing). The application of this technology for the geopolymers was the second innovative aspect. The challenges were related to the automation of the technology (efficiency, zero waste) and its use in harsh Finnish environment (low temperature). The third novel aspect were new products for urban architecture: elements for a skate park and a noise barrier. The design process for these products was supported by new technologies (3D modeling and augmented reality) and actively involved the Lappeenranta city society [8].

Despite difficulties during the project implementation, the project objectives were achieved. The most important was material in line with the circular economy approach and possibly to application of this material in 3D printing technology. The designed geopolymer composite material includes 99.6 % of circulative materials and is 100 % recyclable and printable (Figure 7a). Furthermore, the composite is based on local sources (not more than 100 km), effectively reducing the cost of transportation and CO_2 emissions related to shipping. The planned additive technology was successfully developed. In the laboratory for testing materials, the robotic arm was used. For scale-up, a new solution, a large format 3D printer, was developed, where prototype elements were performed. Both new products were designed and produced. They were dedicated to urban architecture. They were characterized by aesthetic and safe multifunctional structures through a new kind of shape, they increase attractiveness of the city. One of these products, a noise barrier (100 m in length), is presented in Figure 7b.

Additionally, the business model for a new branch was created that will be based on this project, taking into consideration the closed-loop circular economy. This model estimates that the implementation of the results of this project will generate 50-200 new jobs directly or indirectly to local industrial organizations over the next 5-8 years [72].



(a) (b)

Figure 7. Urban infra revolution project: (a) Diagram for presenting the idea of circular economy applied in the project. *Source: [73]*, (b) Final result of the project – noise barrier made in 3D printing technology *Source: [72].*

Case study of hybrid materials for 3D printing of residential houses

The interesting solution was implemented in the project entitled "Development of 3D printing technology for construction and facade prefabricated elements made of concrete composites and geopolymers" funded by the Polish National Centre for Research and Development with using found from the European Union. This project was realized between 2019 and 2022 by Polish University and SME company. The main aim of the project is the design and development of the innovative large-format printer using geopolymers for 3D printing for residential houses (ready components for production of residential houses in place). Total value of the project was: ca. 1 784 050.00 EUR co-financing: ca. 806 342.38 EUR. The original conception was printing the building element on heated plate in horizontal way (max. high—50 cm), however this idea had been changed during the project [15,74].

The first laboratory trials in presented project (testing materials) were made on modified 3D printer for concrete – WASP 2040 with pneumatic feeder. For the scale-up technology the large-format printer was used - ATMAT Galaxy 3D printer (ATMAT, Cracow, Poland) [15,74]. During the research related with materials design for the additive technology, some challenges appeared. The most important was connected with paste liquidity. It was solved by optimization liquid and solid ratio and creating the hybrid material, that included geopolymer and concreate components [15,74,75]. The geopolymer ingredient based on fly-ash or metakaolin as a raw material [15,74]. The changes in materials required were strictly related to the additive manufacturing process, including parameters such as print speed, the thickness of the layer, and print nozzle geometry [74,75]. Despite some difficulties the construction elements with complex geometry has been obtained – Figure 8.

(a) (b)

Figure 8. 3D printed elements developed in the framework of the project: (a) the element with visible layers, (b) the element compared to the human scale. *Source: Own.*

Although the laboratory investigation show a slight difference between the compressive strength of materials developed by casting and additive manufacturing technology [8,76]. The semiindustrial trials show that this difference is quite huge – the values for the compressive strength for 3D printed samples are approximately 40% lower than for cast samples [74]. This phenomenon was limited when the geopolymer based on fly as a raw material was used instead of metakaolin (the difference was approximately 20%) [74]. The investigation also confirms dependence on the direction of the mechanical properties in 3D printed samples – the compressive strength in the perpendicular direction was approximately 10% lower than for parallel direction [74].

Opportunities and barriers to the use of additive technologies in construction
The technology of additive manufacturing gives new perspectives and opportunities in the construction industry. It brings a lot of benefits that may be categorized to four main groups, as follows:

- Design complexity, including more interesting architectural shapes, aesthetic architectural products (create irregular and exotic contours) as well as possibility of construction in harsh environments;
- Reduction of labour costs and increasing the productivity, possibility to eliminate the need for large staff to create features such as concrete walls [29,76];
- Time savings and cost reduction, especially by preparing prefabricated structural elements that are assembled on-site; it is estimated that with implementation the production technology can reduce the cost of materials and labour by up to 80% [76,77];
- Sustainability – reduced environmental impact, including waste minimization.

However, the application of 3D printing technology in construction industry has a lot advantages, it has also some limitations. Some of them are connected with the lack of maturity of this technology that is applied only about a decade to full-scale applications. The most important factor related to the current state of this technology is the sheer size of the printers [78,79]. The limited size of the device have influence on the limitation of the size predicted construction [78,79]. Fortunately, the new technical solutions in 3D printing systems partially overcome this limitation and give new perspectives [79].

Another barrier to a wide implementation of additive manufacturing in the construction industry is the appropriate material. However, good knowledge about plastic behavior in the 3D printing process of the printing concrete, its composites and similar materials is still a challenging task [29,79], including problems related to interlayer bonding [80]. Cementitious materials in this aspect are up-to-date and an important research topic. Concreate is not the only one material that cause the most problems with the application. Even more problematic to application in this technology are wood or steel used as the traditional building materials in the construction. Additionally, even modern devices are limited to printing only one type of material at a time [79,81].

The other element that hampers the creation of genuinely 3D printed structures is building standards and regulations, and, in fact, the lack of appropriate legal regulations in the field of 3D printing in construction. Currently valid building codes and procurement standards do not include additive technologies as building technology, especially some elements such as foundations. It makes it challenging to implement 3D printing in a wider scale. Also, this problem affects building elements and components [82–84], including lack of proper standards for material testing. These types of standards and regulations are necessary to implement large-scale construction projects legally.

Impact
The assessment of the potential impact of use of additive manufacturing of concreate materials in the construction industry is a complex problem. Some of the described case studies for prototype construction clearly showing the positive economic and environmental impact of reduction of costs and wastes reduction [71,84]. However, one should be aware that this influence estimated for this investment usually does not takes into consideration the indirect costs such as training proper workers with knowledge about high technologies and development of modern equipment and software necessary for this kind of investment. Additionally, in this estimation, the problems with durability of the materials are omitted. This is because 3D printing is a relatively new technology and this kind of investigation is based only a laboratory research [85,86]. Although the estimation of economic and environmental impact is not a trivial tasks. Even, the more complicated issue is estimation of the implementation of social impact of the 3D printing technology in construction industry. On hand in can influence on the decrease in price on the construction market and the increase in the availability of residential houses, but a wider adaptation of this technology can decrease the value of the entire market.

Cheap and easily available houses can cause a tendency to more often changing a house and create the large amount of unsettled objects in some areas. On the other hand, the cheap technology can be perceived as a worse one and only as a temporary solution. Regardless of the scenario that will occur in the future, it is worth noting that 3D printing has a huge potential to be breakdown technology in the construction industry in some next decades.

Conclusions

Today, only a few prototype applications of additive manufacturing technologies have been developed in the construction industry. However, 3D printed technology has great potential in this area because of its effective application on an industrial scale, although it still requires development and optimization. The article clearly showed the advantages of the broader applications of 3D printing and successful implementation in various areas of the construction industry. It also indicates that this technology requires a lot of work to be fully effective. The main challenges are connected with scaling up the technology from the laboratory to a fully effective method of industrial production.

Conflict of interest

There are no conflicts to declare.

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