ROBOTICS, AUTOMATION AND MATERIALS FOR ARCHITECTURE

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ABSTRACT: The architecture and construction industry is about to take a big development leap, due to massive robotization, automation and technological and social changes. Our buildings will face new challenges, both in the form of construction and architecture. In the context of current issues, the society is looking for efficient working methods and materials for these modern buildings. This paper deals with the comparison of currently available materials for additive manufacturing using automated processes in the construction industry. As a basic topic of the article, 3D printing of earthen building material is described in depth. This basic material (in several variations) is compared with other building materials that may also be suitable according to the set evaluation criteria. The main factors for evaluation are economics, ecology, technological properties of the mixture, difficulty in carrying out the construction or time. We will also compare materials commonly used for 3D printing today based on concrete, earthen material, metal and plastic. The conclusions presented in the paper will be further used in the specific research project „Earth for People" and follow-up research at the Faculty of Architecture of Brno University of Technology.

KEYWORDS: industry 4.0; automation; robotics; additive manufacturing; materiality; global issues; architecture

INTRODUCTION

Today's world and society is facing new challenges, including the depletion of natural resources, labour shortages, lack of suitable housing, and new technological opportunities [1,2]. In the context of these global issues and new technological opportunities, we are beginning to see robotization, automation and A.I. not only in civil engineering but also in other industries. All these, including other phenomena, are usually unified under the name Industry 4.0 [3]. Today's research on the possible production of structures most often points to the process of additive manufacturing (controlled layer formation of a material) using semi-automated machines. 3D printing is one branch of additive manufacturing in which the controlled layer formation of material into a desired volume is involved. This volume, or better the geometric shape of the resulting object, is created with the help of 3D modelling, scanning of the desired object, artificial intelligence, etc [4]. Another manufacturing option is the subtractive manufacturing process, in which the material is removed in stages. The main disadvantage of the subtractive process is the large amount of residual material.

In general, the most commonly used materials for additive manufacturing are plastic, glass, metal, earth, stone or concrete. Devices designed for layered manufacturing can be divided into stationary (free-standing, placed on a running platform or fixed to a base) and mobile (most commonly wheeled, e.g. robotic arms designed to move, autonomous vehicles). Other robotic arms are classified according to their use (floating, flying, etc.) In today's civil engineering research, stationary robotic arms are most commonly used because of the cost of the equipment or low error rate. These devices most often produce models in concrete or earth, but occasionally plastic, metal or other materials can also be used.

3D printing can be seen as a developing industry and we have already summarized the basics of this issue in the article Additive manufacturing in construction using natural materials [5]. The aim of this paper is to compare the most commonly used materials for 3D printing, which are concrete, earth, metal and plastic according to our chosen criteria and to highlight the materials that seem to be the most suitable for future use in construction practice. For the time being, the most commonly used stationary arm technology has been selected for evaluation and comparison of materials with respect to the environmental, technological and physical aspects. On a practical level, the FA BUT is currently printing test objects from earth on a six-axis robotic arm.

The use of earth in the civil engineering industry as a progressive material with great potential is being investigated by the authors of the article within the framework of several research projects, which are being carried out simultaneously at the Faculty of Architecture of Brno University of Technology. "Earth for People. Ecological and economically friendly community constructions from earth." [6], "One of the most endangered groups in the Historical Building Fund of the Czech Republic: unique technologies of earth buildings using piece building materials (mud lumps) and ways to save them." and "BIOM. "

WHAT MATERIALS ARE USED FOR 3D PRINTING. TYPICAL TECHNOLOGIES AND EXAMPLES OF BUILDINGS.

In today's architecture and construction industry, the most common materials used for 3D printing objects are concrete, earth, metal or plastic. Each material has its own specifics, to which the technologies for production and construction sites are adapted. Today's research mostly works with technology that is based on a proven method of material extrusion namely FFM / FDM (Fused Filament Fabrication/ Fused Deposition Modelling). This involves extruding the material through the nozzles of different thicknesses. This is usually chosen according to the detail required in the final product. Today, the most widely used machines in laboratories and research facilities are industrial multi-axis robotic arms (using running gear for greater serviceability, such as the robotic station at FA BUT in Brno), cartesian (gantry) machines or Scara robotic arms. Each technology is primarily designed for a different material.

CONCRETE

Basic issues of 3D printing from concrete

Devices for 3D printing from concrete, are ranging from the most commonly used 3D printer is called D-shape, from 3D Concrete printing up to new technologies (e.g., printing dry cement mixture that is hardened with water in layers) [7]. These technologies have already been tested in operation and are able to print without formwork components, supports or the requirement to compact the concrete by vibration. The mechanical and physical properties of the printed product are dependent on the chemical composition of the mix used for extrusion [8]. Furthermore, the chosen parameters of the given mixture (printing speed, extrusion of materials, resting time for solidification, distance of the nozzle from the printed shape or the designed geometry of the object) must be optimized. A major issue are the mechanical properties of the resulting concrete, as many voids are usually created in the mix during the printing of the individual layers. If we do not have a machine-mixed mix, it is always necessary to optimise the printing parameters of the machine (speed, passes or layer height).

The material itself (concrete mix) for 3D printing must be modified to have a higher initial strength and shorter setting time compared to the commonly used mix for standard reinforced concrete [9]. Due to the full automation of construction, we do not want to introduce other technologies (reinforcement, formwork, etc.) into the production process. The mixes that make this possible are specially modified and we add reinforcing fibres (carbon, glass or basalt, for example). These admixtures improve the tensile and flexural strength of the resulting material without significantly changing the compressive strength [10]. These specific requirements for the concrete mix cause the price increase of the final product. As a consequence, it is at an economic disadvantage compared to today's standardized work practices. Another problematic part is the bonding of the layers together, which exhibits lower strengths than the base material. A large number of voids and inhomogeneities are formed in the lay-up of the layers, resulting in different physical properties of the final product in different directions. This creates an inhomogeneous material with weaknesses at the joints between the layers. Research has shown that the mechanical strength of concrete is dependent on the orientation and loading of a given printed layer [11].

3D printing of concrete in practice

Today, the standardized and most commonly used printing method is the extrusion of a thin cement-based material by a multi-axis industrial robotic arm (stationary or travelling). This method has been tested, is used commercially and is used in the Czech Republic by companies such as ICE Industrial Services, 3 Deposition or the universities of Brno University of Technology and Czech Technical University in Prague. However, for the reasons mentioned above, new 3D printing methods and mixtures are now being tested to bring new solutions and applications into practice. One of these methods is Contour Crafting and D - Shape. Contour Crafting - this is a method that is being researched by Behrokh Khoshnevis from the Institute of Information Sciences at the University of Southern California. It is a multi-material technology that first prints the outer shape of a part of the structure and then fills it with the concrete material continuing to the next part of the structure. This technology is also being explored in the context of printing new structures that will be used to protect humans colonizing planets [12].

Fig. 1.: Printing technology Countour. (Source: Crafting, C., 2017. Countour crafting for space aplication. Countour crafting. Available at: https://www.contourcrafting.com/space [Accessed June 30, 2023])

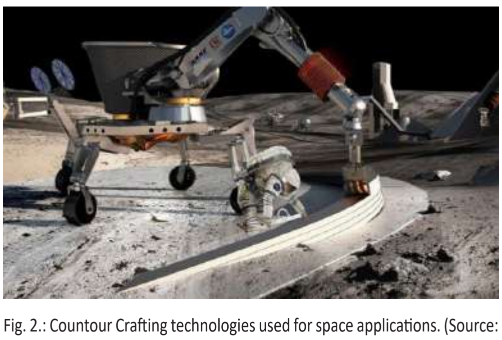

Fig. 2.: Countour Crafting technologies used for space applications. (Source: Crafting, C., 2017. Countour crafting for space aplication. Countour crafting. Available at: https://www.contourcrafting.com/space [Accessed June 30, 2023])

One of the other technologies tested is D-Shape. This is a three-dimensional printer that prints in layers, using sand as the filler, a carbon-based binder and curing with inorganic seawater. The final structure should resemble stone as closely as possible [13].

Fig. 3.: Radiolaria pavilion using D - Shape technology. (Source: Shiro, studio, 2009. Radiolaria pavilion by Shiro Studio. Dezeen. Available at: https://www.dezeen.com/2009/06/22/radiolaria-pavilion-by-shiro-studio/ [Accessed June 30, 2023])

Concrete is one of the most widely used and popular building materials used in architecture and construction today. We, however, are still unable to optimally recycle and reuse this material at low cost. In the context of today's issues (depletion of natural resources, overheating of urban areas or increasing greenhouse gases production), we need to think more comprehensively about whether the concrete is a suitable material for the 21st century along with its use for 3D printing technology [13]. New research projects are trying to work with these problems and find optimal answers.

The future of 3D printing from concrete

Researchers at UC Berkeley have introduced a new method of 3D printing from concrete with minimal waste. This method applies cement powder in the first stage, which is cured with water in the next one. Curing takes place after each layer. This university created an experimental pavilion (Figure 4) that consisted of a total of 840 printed blocks and the entire construction took almost a year [7].

Research at the Self-Assembly Lab at the Massachusetts Institute of Technology, in contrast, looks at the recyclability of buildings printed from concrete.

Fig. 4.: Pioneering research at UC Berkley using powder-based material. (Source: Williams, A., 2015. Berkeley researchers pioneer new powder-based concrete 3D printing technique. New atlas. Available at: https://newatlas.com/berkeley-researchers-pioneer-powder-based-concrete-3d-printing/36515/ [Accessed June 30, 2023])

Experts have come up with a technology that can be printed and dismantled without wasting or hoarding material. The researchers were inspired by the commonly used powder 3D printing technology (SLA/SLS some of the most used technologies in today's 3D printing workplaces). The robot places the filler (aggregate) and connects it with steel wire in each layer. The authors hereby present a new way of environmentally friendly, recyclable and renewable 3D printing that answers today's questions about the self-sufficiency, sustainability and recyclability of our buildings [14].

Fig. 5.: Additive manufacturing using reversible concrete. (Source: MIT, 2015. Reversible Concrete. Web urbanist. Available at: https://weburbanist.com/2015/10/10/reversible-concrete-3d-printing-for-easy-deconstruction-reuse/ [Accessed June 30, 2023])

METAL

Basic issues of 3D printing from metal

Today's technology industry doesn't work much with 3D printing of metal parts, components or parts for architectural structures. The main disadvantages are the high economic costs and difficult to predict defects in the final products. These defects are very often an integral part of products produced using additive manufacturing. For these reasons, metal is not the main domain of today's 3D printing research institutes and the construction industry is no exception. However, within the European Union, we can mention the Intergrade project [15], which deals specifically with metal 3D printing. The aim is to link the entire production process from design to the production. A part of this project is the company MX3D, which deals, among other things, with structures that are suitable for the architectural and construction sectors. The company's research projects show what is possible with this material. In their portfolio we can find, e.g. joints for the construction industry, a bridge, printing solutions for designers or a floor for a lunar module [16]. The researchers state that 3D printing from metal will increase design flexibility, design variety, production efficiency, reduce carbon dioxide production or optimise the use of the material. Research points to these benefits mainly in the use of this technology in the aerospace industry, where it is expected to save up to 90% of the materials used.

The technology for producing the metal product is similar to other materials, the metal is being added in layers using melting with precise placement of the metal wire until the desired shape is achieved. MX3D states that we can use the following 3 types of welding for printing.

1. MIG – offers high speed production, usually used to print larger parts without the need for a closed chamber, relatively easy to produce

2. CMT – similar to MIG with lower production speed but lower process error rate

3. TIG (GTAW) - offers higher product quality during processing, need for manual/automatic rotation of the mechanism when feeding the wire during the production process.

3D printing from metal in practice

Researchers from the Joris Laarman lab wanted to create a project that would display all aspects of MX3D's technology. They came up with the idea of creating a bridge over a canal in Amsterdam that would connect the city's history with the technology of the future. The authors say that after a long process, they finally succeeded. The form of the bridge is designed to be convenient for 3D printing from metal. The researchers were able to optimise the form appropriately using intelligent tools, this results in reducing the material used to a minimum. The bridge is 12.5 m long and 4.5 tons of steel was used [17]. In addition, the project, which has the name "Smart bridge", follows its characteristics, which can be seen in its digital twin online (https://www.smartbridgeamsterdam.com/#bridge). This will help, according to the authors, for future developments.

Fig. 6.: Metal bridge created using 3D printing. (Source: MX3D, 2019 Smart bridge (Source: Smart bridge, 2019. In: MX3D [online]. Amsterdam: MX3D. Available from: https://mx3d.com/industries/design/smart-bridge/) [Accessed June 30, 2023])

Another MX3D project is a skeleton floor for the ESA lunar station, in collaboration with architects Skidmore, Owings and Merrill, which was exhibited at the Venice Biennale 2021. The floor was printed using the GTAW method in stainless steel in impressive 246 hours. 395kg of steel was used for the 3D printing and the final product was 4.5 metres in diameter. Again, the designers analysed the structure to use as little material as possible and to meet all the constraints imposed by the metal 3D printing method [16].

Fig. 7.: Metal bridge created using 3D printing. (Source: Crafting, C., 2017. Countour crafting for space aplication. Countour crafting. Available at: https://www.contourcrafting.com/space [Accessed June 30, 2023])

PLASTIC

Plastic is the most commonly used material in industrial 3D printing of small products due to its undeniable advantages. This material is highly recyclable, reusable, has good filament extrusion properties and is very fast rigid after extrusion. We are able to use a large variety of plastics for printing or use this material together with composite materials. In architecture and construction, we are not yet using the full potential of this material, as it has very different properties from standard materials and the necessary research and management processes towards the certification are very lengthy in our industry [18]. It is the recycling of this material that inspires many researchers, especially in the development of formwork for reinforced concrete structures. This is because traditional formwork accounts for up to 40% of the total budget of reinforced concrete monolithic buildings, and by using a plastic form we are able to optimize the amount of concrete and shorten the schedule without increasing the cost [4,19]. The new design methodology using intelligent tools allows us to use new forms of formwork that offer recyclability, new aesthetics, great material savings or reusability [19,20].

Another innovative feature is the use of plastic material as a 3D printed structure in the space, which serves as a support structure for the application of concrete (e.g. by torquing), without the need for additional formwork [21]. The surface is subsequently smoothed. Again, there are limitations and difficulties with these systems as well. An interesting finding was that the presence of mesh increases the tensile strength of concrete and can be a substitute to the conventional steel reinforcement [22].

In today's literature, many new structural elements and architectural forms using the aforementioned 3D printing methods with plastic material [23] are appearing. Unfortunately, nowadays we have not reached the application to the real operation. One of the many reasons is the unsuitability of the material used or the paradigm of today's architectural processes, both from the design side and from the investors' side. The problem with today's research is that most of the additive processes have focused on the production of concrete mix-based load bearing elements [24]. For these, above mentioned, reasons, we are unable to objectively evaluate the contribution of other materials. The research by Labonette et. all states that we should go in two directions in the future:

1. Research should investigate additive design processes for inhomogeneous materials to facilitate the production of versatile building materials [24].

2. Today's research should develop new innovative materials that exhibit a good combination of all the basic material properties. Define new materials, then optimise them and apply multi-level analysis to them where appropriate. This would eventually become an important part of the development phase of building materials developed to suit specific structures [24].

EARTH

Earth and its use as a building material dates back to ten to fifteen thousand years BC. It is a material that is easy to use, renewable, mechanically resistant and easily recycled. For these reasons, we still use earth today and it is one of the most commonly used building materials worldwide, although it has been unjustly neglected until recently. In the "Earth for People" project, we are trying to change this established paradigm and highlight its potential both in traditional construction and its place in modern technology.

Currently, small earthen 3D printing machines are used to create ceramics (usually the printing material is based on a special clay that allows firing) and large machines for printing buildings (the printing material is an ordinary earth, but it must meet the requirements for transport and passage through the printing nozzle). Ceramic 3D printing produces small models and objects of daily use as well as design accessories or aids for projection or easier presentation of a building or product. Large machines are already making realistic builds, and they are also able to print from local earth (depending on the type of earth, partial adjustments to the mix may be necessary).

Technologie pro keramický 3D tisk

Forma vstupní suroviny	Typ technologie keramického 3D tisku	Zkratka
Na bázi kaše	Stereolitografie	SL
	Digitální zpracování světla	DLP
	Dvoufotonová polymerace	TPP
	Inkoustový tisk	IJP
	Přímé psaní inkoustem	DIW
Na bázi prášku	Trojrozměrný tisk	3DP
	Selektivní laserové slinování	SLS
	Selektivní laserové tavení	SLM
Hromadné na pevné bázi	Výroba laminovaných předmětů	LOM
	Modelování tavené depozice	FDM

Tab. 1.: Technologies suitable for 3D printing from ceramics. (Source: ZHANGWEI, Chen, 2019. 3D printing from ceramics: A review. Journal of the European Ceramic Society. 4(39), 661-687. Available from: doi:https://doi.org/10.1016/j.jeurceramsoc.2018.11.013)

Solid-based materials are generally used for architecture and construction, and FDM is the most widely used technology. For this technology, the following machines are currently most commonly used: stationary printers, industrial multi-axis robotic arms, autonomous vehicles or drones [26]. The technology with industrial robotic arms for small models is also used at our department within the Institute of Experimental Design at the FA BUT in Brno under the direction of B. Arch, Martin Kaftan, Ph.D. We are currently in test operation (Fig. 8,9).

The initial tests were conducted under the following conditions:

1. Kuka industrial multi-axis robotic arm

2. Extruder holder modelled and produced on a Stratasys F120 industrial

3. Eco extruder Lutum with earth tray

4. Printed at standard room temperature

5. Moisture of the earth was not directly measured

6. The models were produced in Rhino software, the print program was created in Grasshopper software and exported in KRL (Kuka Robot Language).

Participants of 3D printing tests: Martin Kaftan, Marco Palma, Efilena Baseta, Jakub Brahmi, Roman Bolcek

Fig. 8, 9.: 3D printing, Institute of Experimental Design, FA BUT Brno. (Source: Bolcek, R. 3D printing by robotic arm [foto]. FA BUT Brno 2023. In: Roman Bolcek Archive [Acessed. June 8, 2023])

Over time, it has been shown that earth (clay) has good results even in additive manufacturing. The clay-like material is easy to fill into the print tray, does not require highly trained forces to prepare the material, is fully recyclable, inexpensive, mechanically durable, easy to print, fully natural and aesthetic at the same time [25]. The disadvantages are the use in small scale project, the need for supports (these can of course be recycled and reused), slow printing speed (material takes a long time to dry), the frequent occurrence of air bubbles (causes gaps in the cartridge, if not filled by machine we cannot achieve optimal results) and the need for manual operation of the arm to optimize the machine parameter (operator manually optimizes the printing speed or height above the printed layer) [25].

All the advantages and disadvantages of printing from this material can only be confirmed after deployment in live commercial operation. We are currently testing the structures on a smaller scale and testing different moisture blends (we are recording the results and plan to continue applied research in the future). After a few tests, we will probably focus on design products. Unfortunately, we do not have the space and economic background for large-scale technology nowadays.

3D printing from earth in civil engineering practice
Basic research and technology for 3D printing from earth in the civil engineering and architectural sectors is being developed by 3D WASP, which for example was the first to print an earthen house using its equipment (Crane WASP 3D). Their equipment is modular, so they do not have to limit themselves to horizontal dimensions, but the printing height is limited to three metres. They created a house called Tecla (technology of clay) [26].

In 2021, the company completed the Dior pavilion, which uses the same printing system (Crane Wasp) as the aforementioned Tecla house. The aim of the project was to reduce the environmental impact compared to traditional technologies or 3D printing from concrete. The structures of the Dior pavilion were built by two simultaneously printing arms. The total area of the building is 80 square meters and 55 tons of printing material was consumed. The total production time took 120 hours. Most of the other projects use similar technology, as 3D WASP is one of the few companies that produce large-scale prints for architecture and construction [26].

Fig. 10.: 3D Printed Earthen Pavilion for the fashion company Dior. (Source: 3D WASP, 2021 Concept store Dior, 2021. In: 3D Wasp [online]. Italy: 3D Wasp Available from: https://www.3dwasp.com/en/3d-printed-pop-up-store-wasp-dior/) [Accessed June 30, 2023])

Scientists at the Institute for Advanced Architecture in Catalonia (IAAC) wanted to create a prototype 3D printed wall that would introduce earth as an acceptable construction material, all with the help of additive manufacturing and an optimised production process. The wall consists of individual modules. In tests, they demonstrated that a local material coupled with a digital process will yield the desired result [26].

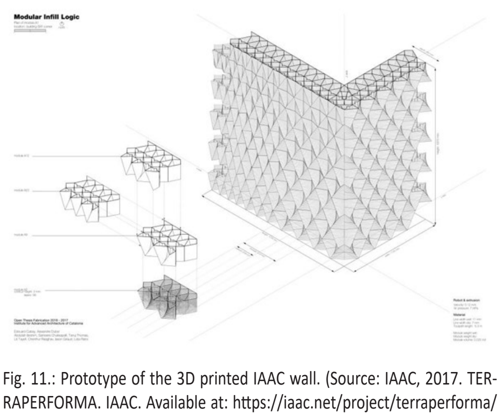

Fig. 11.: Prototype of the 3D printed IAAC wall. (Source: IAAC, 2017. TERRAPERFORMA. IAAC. Available at: https://iaac.net/project/terraperforma/ [Accessed June 30, 2023])

It's no wonder that WASP and IAAC have joined forces to present an innovative wall prototype (designed by IAAC, implemented by WASP) as part of Open Thesis Fabrication research focused on additive manufacturing in the construction industry. This is a continuation of the earthen wall printing research mentioned above. The researchers state that this is an affordable alternative to today's building systems. The 1:1 prototype is a 400 mm thick wall with timber walkable elements. The printing process took 40 hours and used 2 cubic metres of material. The authors state that this is the first significant step towards the realisation of load-bearing structures from this natural material. If we, however, compare such a product with traditional construction technology, the process is still very lengthy [26].

Fig. 12.: Prototype of a 3D printed earth wall. (Source: 3D Wasp, 2022. 3D printed earth wall with embedded staircase. 3D Wasp. Available at: https://www.3dwasp.com/en/3d-printed-wall/ [Accessed June 30, 2023])

Today's technological advances in additive manufacturing using earth are enormous. However, researchers Chen et. ali. emphasize that there are still barriers to optimizing parameters and post-processing for wider use of earth 3D printing. Industrial large-scale production can be very challenging, and high-volume prints are rather rare today. Again, they stress the importance of developing research on the materials in question to progress in the future, as with previous

Materiál	**Výhody**	**Nevýhody**
Beton	Rychlost tisku, zařízení pro velkoobjemový tisk	Občasná nutnost bednění/dodatečné výztuže
	Mechanické vlastnosti	Náročná recyklace
	Nejrozšířenější výzkum	Vysoká produkce oxidu uhličitého
	Dnes již cenově dostupné hmoty pro tisk, pokud neobsahují speciální vláknité materiály (výztuž)	Zasychání hmoty v trysce, nutnost speciálních směsí s urychlovačem tvrdnutí.
	Možnost kombinace s jinými materiály	Nutnost dodatečných úprav pro zisk estetického povrchu.
Kov	Rychlost tisku	Velmi drahá cena materiálu
	Úspora materiálu	Kazy v tisku, těžká opracovatelnost
	Možnost nových tvarů	Nutnost uzavřených komor pro tisk u některých technologií
	Vysoká mechanická odolnost	Vysoké teploty při zpracování materiálu
Plast	Rychlost tisku	Nedostatečné mechanické vlastnosti
	Možnost prostorového tisku	Nedostatečná odolnosti proti klimatickým vlivům
	Recyklace materiálu	Ne-ekologický
	Nízká cena	Vysoká teplota a výpary při tisku, nutnost rovné podložky a uzavřené místnosti
Hlína	Plně přírodní, ideální do míst se špatnou dostupností průmyslově vyráběných stavebních hmot.	Pomalý tisk. Nestálost v kontaktu s vodou.
	Zdravotně nezávadný, jednoduchá manipulace a opravy bez nutnosti speciálního nářadí.	Pomalé tuhnutí, výskyt vzduchových mezer
	Plně soběstačný a recyklovatelný	Častá kazivost výtisků
	Možnost recyklace podpor s následným využitím tisku	Velmi obtížný / vysoce nákladný velkoobjemový tisk

Tab. 2.: Summary of advantages and disadvantages of the materials. (Source: Authors)

materials (metals, plastic, concrete). We must continue to emphasize the production of high performance components, in pure form, and reduce today's costs and overall production time. If we make a simple summary, then today's production technologies are at a very high level, but we are lagging behind with research on the materials used [25].

CONCLUSION

The article summarizes the current state of the art in 3D printing and compares the most frequently used materials for 3D printing, which are concrete, earth, plastic and metal. Our conclusions from the research conducted so far are consistent with the research presented in the paper [18,19,24,25], i.e., that today's extrusion equipment for most materials is of a high standard and capable of printing real objects. The reality, however, is that most of today's research facilities are dealing with concrete extrusion, which in our opinion cannot be considered too innovative compared to the revolutionary nature of this technology. Therefore, research should be directed towards the discovery of new or at least evolutionarily modified materials, whether they will be homogeneous or heterogeneous based. From the history and theory of architecture, we know that for a new technology or material is always adapted the form of the building and the whole production sector. Today's additive manufacturing goes in the opposite direction, working with traditional materials and often not even adapting the form of the structure. Today's technologies allow us to topologically optimize the network, production materials and other production mechanisms. Due to the lack of skilled labour, it is problematic to achieve very good results in most cases [18,19,24,25].

These conclusions should be a major challenge for us as architects in the future. In our opinion, the repetition of modernist and simple forms using promising technology and traditionally used materials is the wrong way to think about today's 3D printing issues. Especially when today's research already offers new materials (based on composite materials - carbon fibre etc.) associated with this technology that have the potential to cause a real revolution in the architectural and construction process [23]. It is up to us to decide which path to take.

Other challenges to consider in the future [18,19,24,25]:

• use of additive manufacturing on a closed site / on site

• we should fully automate the production process, incorporating artificial intelligence

• start testing liquid/powder based materials and adapt our technology to this

• start using more collaboration between architects, engineers and builders

• we need to clearly define whether buildings will be assembled with this technology (partial automation) or printed in their entirety (full automation)

• develop a design approach that allows us to work with more of the constraints that are important for today's performance indicators: speed of construction, cost, sustainability, self-sufficiency, durability, pollution or recyclability

• to develop a new way of designing with rules that will directly address additive manufacturing

Additive manufacturing may cause a change in established building and architectural processes in the future [24,25]. All indications are that this will not be the case with traditional building materials (concrete, metal, earth, plastic) that are used today [24,25]. Additive manufacturing with these materials is difficult to compete with traditional and time-tested manufacturing technologies. The extrusion of conventional building materials is economically, time and personnel consuming (need for highly skilled labour) and often does not even achieve the same quality as the standard products produced by traditional methods (casting, folding, welding, etc.). This, however, does not mean that we should not continue research and training in this area. We should be more open and explore new material and technological possibilities of additive manufacturing for construction and architecture [24,25]. This technology has the potential to change the construction industry. It is up to us to make it happen in an environmentally, economically, personnel and technologically sustainable way.

SOURCES

[1] Herrington, G., 2021. Limits to Growth: Comparing the world3 model with empirical data. Journal of Industrial Ecology, 2021(25), pp.614-626. Available at: https://doi.org/10.1111/jiec.13084 [Accessed January 14, 2023]

[2] Meadows, D., Medowsová, D. & Randers, J., 2013. Limits to Growth: The 30-Year Update Paperback., White River Junction, United States: Chelsea Green Publishing Co.

[3] Bolognesi, C. & Santagati, C., 201I9AD. Impact of Industry 4.0 on Architecture and Cultural Heritage: Advances in Civil and Industrial Engineering, Pensylvánie USA: IGI Global.

[4] Prof. Dr. Dillenburger, B., 2020. The future of architecture: 3D printing: Methods of construction have surprisingly barely evolved (Photo: © Tom Mundy, ETH Zürich). Www.lgt.com. Available at: https://www.lgt.com/en/magnet/lifestyle/the-future-of-architecture-3d-printing-00001/#button2 [Accessed October 25, 2021]. https://www.lgt.com/en/magnet/lifestyle/the-future-of-architecture-3d-printing-00001/#button2

[5] Bolcek, R. & Vejpustek, Z., 2021. Aditivní výroba ve stavebnictví při využití přírodních materiálů D. Lehnert, V. Schwab, & P. Hlavsa, eds. Tzbinfo, 2021, pp.1-11. Available at: https://stavba.tzb-info.cz/hruba-stavba/23182-aditivni-vyroba-ve-stavebnictvi-pri-vyuziti-prirodnich-materialu [Accessed January 17, 2022].

[6] Specific research project, FA-S-21-7541 „Earth for people. Ecological and economically favourable community buildings made of Earth material.", Faculty of Architecture, Brno University of Technology. https://www.vut.cz/vav/projekty/detail/32785

[7] Williams, A., 2015. Berkeley researchers pioneer new powder-based concrete 3D printing technique. New atlas. Available at: https://newatlas.com/berkeley-researchers-pioneer-powder-based-concrete-3d-printing/36515/ [Accessed June 30, 2023].

[8] Li, Zhang & Tay, 2022. Chapter 9 - Three-dimensional (3D) printing for building and construction. Digital Manufacturing, pp.345-385.

[9] Perrot, Rangeard & Perre, 2016. Structural built-up of cement-based materials used for 3D-printing extrusion techniques. Metal and Structures, 2016, pp.1213–1220. Available at: https://link.springer.com/article/10.1617/s11527-015-0571-0 [Accessed June 29, 2023].

[10] Le, Austin & Lim, 2012. Hardened properties of high-performance printing concrete. Cement and Concrete Research, 3(42), pp.558-566.

[11] Crafting, C., © 2017. Technologies for Building Immediate Infrastructure on the Moon and Mars for

Future Colonization. Contour crafting. Available at: https://www.contourcrafting.com/space [Accessed June 29, 2023].

[12] Jassmi, Najjar & Mourad, 2018. Large-Scale 3D Printing: The Way Forward. IOP Conference Series: Materials Science and Engineering,, (324).

[13] Kohlstedt, K., 2015. Reversible Concrete: 3D Printing for Easy Deconstruction & Reus. Available at: https://weburbanist.com/2015/10/10/reversible-concrete-3d-printing-for-easy-deconstruction-reuse/ [Accessed June 29, 2023].

[14] Integradde, P., 2018. The INTEGRADDE Project. Integradde project. Available at: http://www.integraddeproject.eu/project [Accessed June 29, 2023].

[15] Anon., 2018. LUNAR FLOOR FOR ESA. Https://mx3d.com. Available at: https://mx3d.com/industries/construction/lunar-floor-for-esa/ [Accessed June 26, 2023].

[16] Mika, O., 2018. Ocelový most pro Amsterdam vyrobený technologii 3D tisku. Materiály pro stavbu, 24(9), pp.44-45.

[17] Huang, Zhongyuan & Xiao, 2016. Highly Informed Robotic 3D Printed Polygon Mesh. Acadia, 16(298), pp.298-307.

[18] Kothman, I. & Faber, N., 2016. How 3D printing technology changes the rules of the game:: 05 Sep 2016, Vol. 27, Issue 7, pages 932 - 943. Journal of manufacturing technology management, 7(27), pp.932-943.

[19] Sgambati III, J., 2023. Could 3D-Printed Formwork Revolutionize Sustainable Construction? Metropolis mag. Available at: https://metropolismag.com/projects/gramazio-kohler-research-3d-printed-concrete-formwork/ [Accessed June 29, 2023].

[20] Busta, H., 2015. This Architect-Designed Wall System Has a 3D-Printed Core. Architect magazine. Available at: https://www.architectmagazine.com/technology/this-architect-designed-wall-system-has-a-3d-printed-core_o [Accessed June 29, 2023].

[21] Norman, H. & Lauer, W., 2014. Mesh-Mould: Differentiation for enhanced performance. In 19th International Conference of the Association of ComputerAided Architectural Design Research in Asia (CAADRIA 2014). Kyoto, Japan: CAADRIA, pp. 139 - 148.

[22] Antonelli, P. & Burckhardt, A., 2020. THE NERI OXMAN MATERIAL ECOLOGY CATALOGUE, New York City: THE MUSEUM OF MODERN ART.

[23] Labonnote, N., 2016. Additive construction. Automation in Construction, 3(72), pp.347-366.

[24] Zhangwei, C., 2019. 3D printing of ceramics: A review. Journal of the European Ceramic Society, 4(39), pp.661-687.

[25] Wasp, project, c2023. 3D Wasp projects. 3D Wasp. Available at: https://www.3dwasp.com/en/projects [Accessed June 29, 2023].

[26] Cabay, E. & Dubor, A., 2017. TERRAPERFORMA: 3D Printed Performative Wall. IAAC. Available at: https://iaac.net/project/terraperforma/ [Accessed June 29, 2023]. -