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THE PHILOSOPHY OF SHAPING SPACE WITH 3D PRINTING

FILOZOFIA KSZTAŁTOWANIA PRZESTRZENI ZA POMOCĄ DRUKU 3D

Abstract

The article discusses the use of large-format 3D printing with cementitious composites in shaping the spaces of everyday life, together with the philosophy accompanying this process. The main objective is to determine what forms can be printed, what materials can be used and what software supports the transition from a digital model to a stable object printed by extrusion.

Keywords: *3D concrete printing (3DCP), additive technologies, architecture, cementitious composites, shaping of space*

Streszczenie

Artykuł podejmuje wykorzystanie wielkoformatowego druku 3D z kompozytów cementowych w kształtowaniu przestrzeni życia codziennego oraz towarzyszącą mu filozofię. Głównym celem jest określenie, jakie formy można drukować, jakie materiały można stosować oraz jakiego oprogramowania należy użyć, aby przejść od modelu cyfrowego do stabilnego obiektu drukowanego metodą ekstruzji.

Słowa kluczowe: *architektura, druk 3D z betonu (3DCP), kompozyty cementowe, kształtowanie przestrzeni, technologie addytywne*

1. INTRODUCTION

Additive technologies, a decade ago associated mainly with prototyping small objects, are entering construction ever more boldly; systematic reviews speak directly of the transformation of the industry by 3D concrete printing.[1] Large-format printing with cementitious mixes shortens construction time from months to weeks, reduces material consumption and waste, and opens up freedom in shaping forms that would be uneconomical or impossible in traditional formwork. This freedom, however, raises questions beyond technology – about the meaning of the space it is to help create.

The paper presents the process of large-format 3D printing with concrete mixes for small-scale architecture. The aim is to determine what forms can be printed and what materials and software are needed to move from a digital model to a stable object printed by extrusion. The review covers cementitious mixes and their additives, conventional and dispersed reinforcement, and digital tools – from BIM modelling to print-path simulation.

The article runs along two tracks: the first situates the subject within philosophical reflection on the experience of architecture; the second, technical, discusses printers, materials and the process from digital model to stable object, complemented by completed projects.

2. THE PHILOSOPHY OF SHAPING SPACE

Reflection on the shaping of space is best begun with the relationship between architecture and philosophy, for this link is neither accidental nor superficial. Architectural theory is largely philosophical reflection in action: questions of proportion, composition or meaning ultimately lead beyond the discipline itself.

Such is 3D concrete printing: innovative – reducing construction time, material consumption and CO_2 emissions; pioneering – from printing text on paper through desktop printers to houses that meet seismic standards; and controversial, like every technology that we are only beginning to domesticate. It is gaining popularity in Western and Northern Europe and in Asia.

How do we experience space at all? Architecture is perceived with the whole body – through sight, but also hearing, touch and smell. Everyone perceives a building differently: we differ in height, in the rhythm of our steps and in sensitivity to sound, and the remembered smell of a grandfather's cellar will one day return when designing a new building. Despite differing needs, architecture unites us in experience: created for a community, it strengthens identity; created for an individual, it expresses that individual.

Architecture does not exist all at once – it reveals itself over time, in sequences, as we traverse it. The user does not so much look at a building as walk through it, and the architect, working with plan and section, records paths of movement and scenarios of perception. Such design resembles a labyrinth – not chaos, but a structure of choices that sustains curiosity and shows the way out.

What matters most are the emotions and meanings that space evokes and preserves. A building may arouse calm or unease, solemnity or intimacy; if it evokes nothing, it is dead.

[1] A.A. Agegn et al., *Systematic review on 3D concrete printing technology: breakthroughs and challenges*, "Discover Civil Engineering" 2026, no. 3, art. 9, https://link.springer.com/article/10.1007/s44290-025-00399-2 (access: 12.08.2026).

Nor is experience ever "pure" – memory interprets, and afterimages of former spaces shape the reading of form and atmosphere: the same space becomes a place of rootedness for some and remains alien to others.

True architecture is therefore a philosophical practice: it materialises ideas and establishes relations between individual and community, private and public, permanent and ephemeral. 3D concrete printing fits this perspective well – a technology that allows one almost literally to "print a thought" demands all the greater intellectual discipline from its author. Whether the result is merely a building or true architecture, only subsequent generations of users will discover.

3. 3D PRINTING TECHNOLOGY

Increasingly, 3D printing is identified as the future of construction – the machine takes over the labour involved in building, and the designer regains freedom in shaping form. Costly formwork and large site crews disappear – complex geometry arises in a single continuous movement of the print head. The literature speaks directly of the revolutionary potential of this technology.[2]

3.1. TYPES OF LARGE-SCALE 3D PRINTERS

Large-scale concrete printers are classified by supporting structure and the way the head is moved: gantry (portal) systems, robotic arms, and crane-based and mobile systems (Ill. 1). Gantry printers move the head in three axes along a rigid frame – this ensures high accuracy but limits the working area to the frame's footprint. It is the solution most often used for entire buildings (Ill. 2), e.g. the BOD2 printer.

Robotic-arm printers use industrial robots on a fixed base or mobile platform. Multi-axis work gives the greatest freedom – allowing rounded and inclined forms that are difficult to produce in a gantry system – while tracks extend the limited reach of a single arm.

In crane-based printers the head is suspended from a construction crane; intended for tall and large-area structures, they face the challenge of stabilising a head susceptible to oscillation under wind.

Experimental methods include the IAAC concept of a "swarm" of small synchronised robots (Foundation, Grip and Vacuum Robot) printing objects of arbitrarily large size.

3.2. MATERIALS

Extrusion-based 3D printing consists of the layer-by-layer deposition of a cementitious composite pumped to the nozzle, combining materials engineering with processing in automated additive construction.[3] One-component (1K) and two-component (2K) mixes are distinguished, the latter with a setting accelerator dosed at the head.

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[2] S. Banihashemi et al., *3D printing in construction: sustainable technology for building industry*, "Progress in Additive Manufacturing" 2025, no. 10(12), pp. 11729–11762, https://link.springer.com/article/10.1007/s40964-025-01314-y (access: 12.08.2026).

[3] A. Hutyra et al., *Review of Material Processing Technology for 3D Concrete Printing*, "Materials" 2026, no. 19(3), art. 564, https://doi.org/10.3390/ma19030564 (access: 12.08.2026).

The mix must combine seemingly contradictory properties: pumpability, extrudability and buildability – retention of layer shape without formwork – as well as an appropriate open time, which studies identify as critical.[4] Pumpability requires a high proportion of fines – hence the high content of Portland cement and mineral additives: silica fume (about 10%), which densifies the microstructure, and fly ash (about 20%), which improves workability. Consistency is regulated with viscosity modifiers and superplasticisers; aggregate is limited to about 2.5 mm, as coarser grains cause blockages and irregular layers.

The research mix includes CEM I 42.5 R cement, limestone filler, 0–2 mm sand, a superplasticiser, and cellulose and polypropylene fibres (0.05% by weight, 6 mm). Ready-made mixes are also available (Sika, Cemex, Mudbots, X-Hab 3D), and the direction of development is set by multifunctional materials combined with 3D printing.[5]



Ill. 1. Dubai Municipality building under construction, printed on site with a mobile Apis Cor printer, Dubai (UAE), 2019. Photo: Apis Cor, source: ArchDaily, https://www.archdaily.com/930857/dubai-municipality-to-become-the-worlds-largest-3d-printed-building/5e01e5223312fdc332000747-dubai-municipality-to-become-the-worlds-largest-3d-printed-building-image (access: 10.09.2026)

Reinforcement in 3DCP may take various forms, and its importance can hardly be overstated: its absence long inhibited the wider adoption of printed concrete.[6] Its choice depends

[4] A.K. Patel, M. Santhanam, *Rheological and Fresh-State Characterization for 3D-Printable Concrete: Evaluating Printability across Different Binder Systems*, "Journal of Materials in Civil Engineering" 2026, no. 38(4), https://doi.org/10.1061/JMCEE7.MTENG-21562 (access: 12.08.2026).

[5] X. Wang et al., *Concrete 3D printing technology for sustainable construction: A review on raw material, concrete type and performance*, "Developments in the Built Environment" 2024, no. 17, art. 100378, https://www.sciencedirect.com/science/article/pii/S2666165924000590 (access: 12.08.2026).

[6] H.-Q. Sun et al., *3D-printed concrete with in-process embedded fiber-reinforced polymer grid re-*

on the forming method and the designed geometry; conventional and dispersed types are distinguished.

Conventional reinforcement – bars, stirrups and meshes – is placed in accordance with or independently of the rhythm of the layers, embedded during printing or inserted before setting. Reviews confirm that steel bars combined with fibres and nanomaterials remain a key strategy.[7] Dispersed reinforcement plays a supporting role, limiting cracking of the hardened mix. Steel, glass, polypropylene and basalt fibres are used, with differing effects on shrinkage, flexural strength and rheology; in the research conducted these are chiefly alkali-resistant (AR) glass fibres 6–12 mm long, which – like the aggregate – must not block the nozzle.



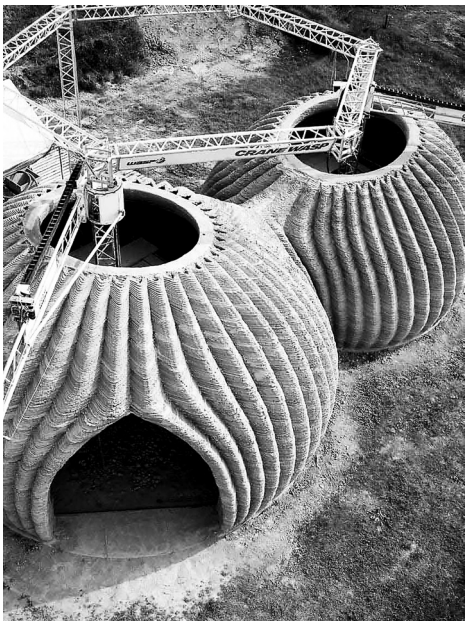
Ill. 2. House in the 3D-printed development in Nacajuca (Tabasco, Mexico), ICON with New Story and ÉCHALE, 2019. Source: Dwell, https://www.dwell.com/article/3d-printed-village-icon-new-story-tabasco-mexico-b76d0150/6610581394988380160 (access: 10.09.2026)

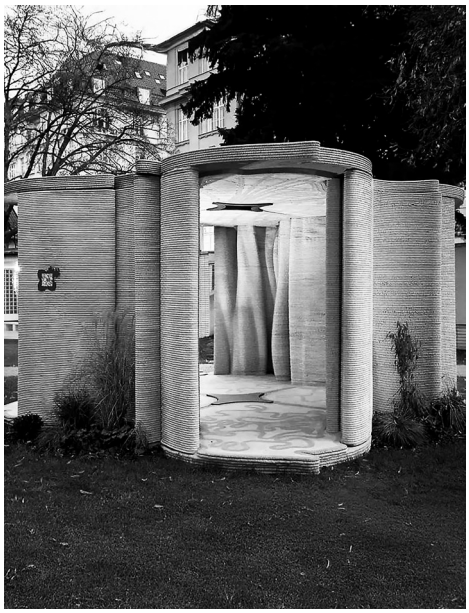
4. FROM A DIGITAL MODEL TO A STABLE OBJECT – THE PROCESS OF FORM CREATION

The transition from digital model to stable object requires a coherent chain of design and technological decisions. In the work carried out it is implemented as a full cycle for objects of small-scale architecture, in parallel with materials research: from concept, through digital model and prototypes at successive scales, to the final 1:1 print.

inforcement, "Communications Engineering" 2026, no. 5, art. 72, https://www.nature.com/articles/s44172-026-00628-1 (access: 12.08.2026).

[7] B. Nan et al., *Advancing Structural Reinforcement in 3D-Printed Concrete: Current Methods, Challenges, and Innovations*, "Materials" 2025, no. 18(2), art. 252, https://doi.org/10.3390/ma18020252 (access: 12.08.2026).





Ill. 3. TECLA – habitat 3D-printed from raw earth, Mario Cucinella Architects and WASP, Massa Lombarda (Italy), 2021. Photo: Iago Corazza, source: ArchDaily, https://www.3dwasp.com/en/3d-printed-house-tecla/ (access: 09.10.2026)

Ill. 4. Pavilion Between Conflicts – 3D-printed concrete pavilion based on the modular MoDeSty system, Coral Construction Technologies, Designblok 2022, Museum of Decorative Arts garden, Prague. Source: Coral Construction Technologies, https://www.coral3dcp.com/projects/pavilion-between-conflicts (access: 10.09.2026)

The starting point is a concept developed as a BIM or parametric model, exported as STL geometry, divided into layers and simulated in slicing software (OrcaSlicer, Cura). The path is not neutral – the direction of layer deposition determines the strength anisotropy of the element, and path optimisation is a separate strand of research.[8] Already at this stage the limitations of the technology – overhangs and wall inclinations, curvature radii, supports and services – can be assessed in simulation. Artificial intelligence plays a growing role here and is identified as the solution to these bottlenecks.[9]

The first physical verification is a small PLA prototype tested for geometry and form stability – a fast, inexpensive stage that catches design errors before the concrete mix enters the process.

The verified design is printed at about 1:20 scale in the concrete mix. Layer height and width, head speed and interlayer time are calibrated – too short an interval deforms the lower

[8] Z. Zhuang et al., *A comprehensive review of sustainable materials and toolpath optimization in 3D concrete printing*, "npj Materials Sustainability" 2024, no. 2, art. 12, https://doi.org/10.1038/s44296-024-00017-9 (access: 12.08.2026).

[9] L. Wang et al., *AI-powered 3D printed concrete technology: a new paradigm of intelligent construction integrating materials, equipment, and structures*, "AI in Civil Engineering" 2026, vol. 5, art. 19, https://link.springer.com/article/10.1007/s43503-026-00104-x (access: 12.08.2026).

layers, too long weakens the interlayer bond. Shape stability is examined by the two-layer method or by analysing the deformation of test models.

Research on the mixes runs in parallel; here too digital tools enter – mix design requires interpretable models optimising strength, printability and durability.[10] Mechanical properties are verified on specimens cut from printed elements or on cubes cured under controlled conditions (24 h under film at 20 ± 2°C, then in water until day 28). Because of anisotropy, they are tested in three directions (X, Y, Z). Similarly, the bond between FRP bars and printed concrete proved lower than in cast elements.[11] Only such data make the object structurally predictable and the process repeatable.

The sequence concludes with the 1:1 print, on site or in the laboratory, from which the object is transported to the plot.

The scale of small-scale architecture (Ill. 4) allows the whole process from idea to print to be run – each object is at once a design exercise and a research specimen, and confrontation with site, users and budget is the final mediation between vision and reality.

5. COMPLETED PROJECTS

3D printing already has a first generation of completed objects showing the full spectrum of applications; a global survey covers 154 projects and 204 buildings from 2013–2023.[12] Residential examples include the TECLA houses in Massa Lombarda, printed from local raw earth (Ill. 3), the houses in Beckum and Milan and the WinSun structure in China. A different scale is represented by the Dubai offices: the Office of the Future – the first permanently occupied printed office, at half the conventional cost – and the Apis Cor building, the largest printed to date (640 m², Ill. 1). The technology has also proved itself in hotels (Lewis Grand Hotel, Philippines), social housing (ICON in Tabasco – a 48 m² house in a day, Ill. 2) and infrastructure – from the steel MX3D footbridge in Amsterdam to the concrete footbridge in Nijmegen.

One of the most advanced examples is the Striatus Bridge – an arched footbridge of 16 × 12 m by Zaha Hadid Architects, the Block Research Group (ETH Zürich), Incremental3D and Holcim, presented at the Venice Architecture Biennale in 2021. Its compression-only design dispenses with steel reinforcement and reduces material consumption. Its 53 prefabricated blocks follow the principal compressive stresses in their print path, limiting anisotropy. Assembled dry, without mortar, it is stabilised by the arch geometry and steel tie rods, so it can be dismantled and reused.

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[10] Y.M. Abbas, A. Alsaif, *Explainable Data-Driven Modeling for Optimized Mix Design of 3D-Printed Concrete: Interpreting Nonlinear Synergies among Binder Components and Proportions*, "Computer Modeling in Engineering & Sciences" 2025, no. 145(2), pp. 1789–1819, https://doi.org/10.32604/cmes.2025.073088 (access: 12.08.2026).

[11] J.-J. Zeng et al., *Bond performance between FRP bars and 3D-printed high-performance concrete*, "Structures" 2025, no. 73, art. 108377, https://www.sciencedirect.com/science/article/pii/S2352012425001912 (access: 12.08.2026).

[12] G. Placzek, P. Schwerdtner, *A Global Snapshot of 3D-Printed Buildings: Uncovering Robotic-Oriented Fabrication Strategies*, "Buildings" 2024, no. 14(11), art. 3410 https://doi.org/10.3390/buildings14113410 (access: 12.08.2026).

The common denominator of these projects – regardless of scale, function and material, from cementitious composites through lavacrete to raw earth and steel – is a radical shortening of construction time and a clear reduction of costs (Table 1).

Table 1. Completed 3D concrete printing projects

No.	Name	Category	Location	Material used	Area (m²)	Construction time (days)	Cost (PLN)
1	TECLA	House	Italy, Massa Lombarda	Clay	60	8.3 (200 hrs)	140,000
2	Beckum	House	Germany, Beckum	Concrete	160	4	1,500,000
3	Office of the Future	Office building	United Arab Emirates, Dubai	Concrete	250	17	1,900,000
4	Milan	House	Italy, Milan	Concrete	100	10	300,000
5	Dubai Municipality building	Office building	United Arab Emirates, Dubai	Concrete	640	60	2,300,000
6	House in China	House	China	Concrete	200	45	450,000
7	Lewis Grand Hotel	Hotel	Philippines, Angeles City	Concrete	130	5 (100 hrs)	350,000
8	Housing development in Tabasco	House	Mexico, Tabasco	Concrete	48	1 house/day	80,000
9	Nijmegen Bridge	Bridge	Netherlands, Nijmegen	Concrete	30	90	500,000
10	Striatus Bridge	Bridge	Italy, Venice	Concrete	50	35 (printing: 84 hrs)	n/a

6. DIRECTIONS OF DEVELOPMENT – THE SPONGE BUILDING PROJECT

The SPONGE Building Project (Sustainable Concrete Freeforming for the New European Bauhaus), funded under Horizon Europe, sets the current direction: not a single realisation but a comprehensive system for designing and producing low-carbon architectural elements by extrusion. It integrates parametric design, materials engineering and robotic production in one continuous process, supported by a Digital Twin – a virtual model linked to the object at successive stages, which allows deformations to be predicted, quality controlled and the robot path optimised before production.

In parallel, composites with reduced cement content, more mineral additives and dispersed fibres, including recycled ones, are being developed, cutting CO_2 emissions while maintaining the rheology and strength needed for stable printing. Unlike demonstrators such as the Striatus Bridge, SPONGE aims at a universal design-and-production ecosystem – from BIM model, through robot path and print simulation, to quality control – in the spirit of the New European Bauhaus, where 3D printing is less a method of automating construction than a tool for optimising structure, material consumption and design freedom at once.

7. CONCLUSIONS

The article has addressed the shaping of space by 3D printing along two tracks – philosophical reflection and technological process – and both lead to a common conclusion: a technology that allows one almost literally to "print a thought" does not release the designer from responsibility for the meaning of space, but demands all the greater intellectual discipline.

The technical analysis identifies the conditions for the transition from digital model to stable printed object. First, success is determined by the rheology of the mix – the balance of pumpability, extrudability and buildability – which, as researchers conclude, governs the printability of cementitious composites.[13] Second, reinforcement – above all dispersed glass fibres – is selected together with geometry and print path, because printed concrete remains anisotropic. Third, layer height, head speed and interlayer time require calibration for every mix and form, verified through a sequence of scales – PLA prototype, 1:20, 1:1.

Completed objects – from clay and concrete houses to steel footbridges – show that the technology has left the laboratory. A barrier remains the absence of standards dedicated to additive structures: the literature confirms that the lack of standardised testing and approval procedures inhibits wider adoption.[14] Further work includes strength testing of glass-fibre mixes and – after consultations with municipalities – the first small-scale architecture in public space; smart printed façades also remain a promising field.[15] The goal remains not the technology but the space: 3D printing is a tool for materialising ideas, and the measure of success is whether the objects prove to be true architecture.

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