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FROM ALGORITHM TO EXPERIENCE. DIGITAL FABRICATION OF CONCRETE FORMS IN THE GRASSHOPPER ENVIRONMENT

OD ALGORYTMU DO DOŚWIADCZENIA. CYFROWA FABRYKACJA FORM BETONOWYCH W ŚRODOWISKU GRASSHOPPER

Abstract

The aim of the paper is to present the digital fabrication process of medium-sized small architectural forms using 3D concrete printing – from a parametric digital model to a stable physical object. Complex geometries were generated algorithmically in the Rhinoceros/Grasshopper environment, concrete mixes for layered extrusion were selected, and print paths were verified on PLA test prints. The research results in two print-ready designs, presented in photorealistic visualisations, which demonstrate the potential of algorithmically generated small architectural forms in urban space.

Keywords: *3D concrete printing, Grasshopper, parametric design, small architectural forms*

Streszczenie

Celem pracy jest przedstawienie procesu cyfrowej fabrykacji średniogabarytowych elementów małej architektury w technologii druku 3D z betonu – od parametrycznego modelu cyfrowego do stabilnego obiektu fizycznego. Złożone geometrie wygenerowano algorytmicznie w środowisku Rhinoceros/Grasshopper, dobrano mieszanki betonowe do ekstruzji warstwowej, a ścieżki druku zweryfikowano na

wydrukach testowych z PLA. Efektem badań są dwa gotowe do druku projekty, przedstawione w fotorealistycznych wizualizacjach, które pokazują potencjał generowanej algorytmicznie małej architektury w przestrzeni miejskiej.

Słowa kluczowe: *druk 3D z betonu, Grasshopper, mała architektura, projektowanie parametryczne*

1. INTRODUCTION

3D concrete printing is among the most promising technologies in contemporary construction, offering a genuine alternative to traditional casting techniques. Dispensing with formwork opens up the possibility of freely shaping fluid, organic and individualised forms – difficult or impossible to obtain with rigid shuttering panels. The development of this field is underpinned by the Building Information Modeling (BIM) methodology and by integrated numerical design environments, which ensure a continuous flow of information from the concept through to physical realisation on the printer. Buswell and co-authors, summarising the work of the RILEM TC 276 technical committee, point out that digital fabrication with concrete encompasses many distinct processes – classified as additive, formative and subtractive – and that comparing them is hampered precisely by the interdependence of design geometry, material properties and process parameters.[1] Technology, however, is not an end in itself here – its meaning is revealed only when the printed object enters the space of everyday life and begins to be perceived by people: not only with the eyes, but with the whole body, through touch, hearing and even the memory of places that we carry within us. On a global scale, this technology has already left the experimental phase: gantry printers and robotic arms erect entire residential buildings, footbridges and infrastructure elements.

The present study focuses on small architectural forms of moderate dimensions. This scope makes it possible to optimise prefabrication under workshop conditions and to simplify the subsequent logistics and installation of the elements in public space. The principal research problem is to define the principles of a controlled transition from the digital model to a stable physical object – that is, to link algorithmically generated geometry with the real constraints of the extrusion process, such as permissible overhang angles or the capacity of the fresh mix to bear loads on its own. In parallel, a question is posed about experience: how geometry that the user discovers sequentially, in motion, can build tension and sustain curiosity – for architecture should intrigue rather than offer simple answers. In practice, this means operating within a narrow technological window: the fresh mix must be fluid enough to be pumped and extruded, yet stiff enough that a layer does not deform under the weight of the subsequent ones; excessive offset of the layers relative to one another threatens the loss of stability of the entire body while printing is still in progress.

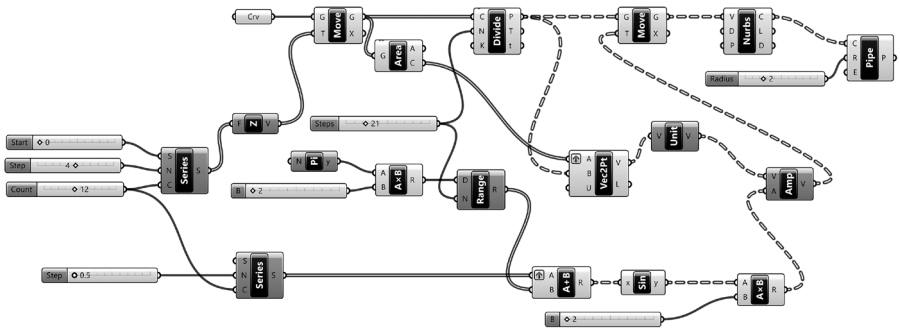
The article discusses, in turn: the method of parametric geometry generation, the mechanisms of form variation, the selection of material mixes, the preparation of the print path together with its verification on test prints, and finally the visualisation of the two developed objects in their target context of use. Running through all the parts is the theme of multisensory perception – the conviction that architecture, including small-scale architecture, is perceived

[1] R.A. Buswell et al., *A process classification framework for defining and describing Digital Fabrication with Concrete*, "Cement and Concrete Research" 2020, no. 134, art. 106068, https://doi.org/10.1016/j.cemconres.2020.106068 (access: 10.09.2026).

with all the senses, and that its form encodes the scenarios of perception of its future users. The adopted method is a research-by-design approach: the successive stages – algorithm, material, slicing, prototype – form a feedback loop in which the conclusions of each phase correct the assumptions of the previous one.

2. METHODOLOGY – GENERATING PARAMETRIC GEOMETRY

The methodology of the study is based on a fully parametric design chain in which the geometry of the object is not drawn directly but is described by a set of rules and variables. This approach shifts the designer's effort from modelling a single form to building a system that generates entire families of forms – from the general logic of the shape to parameters tailored to the constraints of the printing process. The following subsections discuss the digital tools used and the structure of the geometry-generating algorithm itself (Ill. 1).



Ill. 1. Algorithm for generating the planter geometry in the Grasshopper environment. Source: authors' own work

2.1. DIGITAL TOOLS

The design process is founded on the Rhinoceros environment with the Grasshopper plug-in, which enables geometry to be built on the basis of visual algorithms. The print path was prepared in the Orca Slicer slicing software, while the test prints were produced on an FDM printer with PLA filament. Grasshopper is a visual programming environment: the designer does not write code but connects components into a data-flow graph, and every change of a parameter immediately rebuilds the geometry in the Rhinoceros viewport. Orca Slicer, although it originates from the world of desktop printers, operates on the same logic as industrial concrete-printing systems – it divides the solid into horizontal cross-sections and converts them into coordinates for the movement of the print head – so that conclusions drawn from PLA prints can be scaled up to the full-size process.

2.2. THE ALGORITHM IN THE GRASSHOPPER ENVIRONMENT

The entire model is based on a parametric definition that begins with drawing a base planar curve. The defined outline is then successively duplicated along the vertical Z axis, which

constitutes a direct digital simulation of the build-up of successive layers of material deposited by the nozzle. The height of each layer, Z_i, is defined by a simple linear formula:

$$Z_i = i \cdot h$$

where is the index of the successive layer (from 0 to), and denotes the height of a single layer of material deposited by the printer.

The virtual stack of curves built in this way is densely sampled into a set of control points, from which radial vectors are derived that determine the direction and magnitude of the deformation. Introducing into the script modulations based on trigonometric functions (a sinusoid) and modifying the course of the curves with NURBS (Non-Uniform Rational B-Splines) allow the outer shell of the solid to be smoothly undulated and sculpted. The algorithm calculates the displacement value on the basis of three main variables: the wave depth (amplitude) – how strongly the material is pushed outwards; the frequency – how many wave 'bellies' occur along a single perimeter; and the phase shift – a value linked to the layer height, which causes the waves to twist smoothly upwards, creating a dynamic pattern.

The final stage of the algorithmic chain is the materialisation of the path with the Pipe component, which makes it possible to visually assess the thickness of the concrete filament and to detect potential collisions. A similar route – embedding the fabrication logic within the parametric environment itself – has been taken by the developers of plug-ins dedicated to additive manufacturing: VoxelPrint generates in Grasshopper voxel-based computational models ready for analysis in Abaqus, making this procedure available both to designers without numerical training and to advanced users.[2] The Termite plug-in, in turn, embeds slicing operations directly in the parametric definition; its authors argue that conventional slicing programs were designed for nozzles 0.3–1.0 mm in diameter, whereas paste-like materials require nozzles in the range of 1–30 mm.[3]

The undulation and sculpting of the shell are not, however, merely ornamental – they record future sensations: the play of light and shadow on the corrugated surface and a texture that invites touch change with the movement of the observer and the time of day. From a technical point of view, the continuity of the path is crucial: concrete printing favours a single, closed trajectory without nozzle jumps, which is why the algorithm generates the outlines as closed curves, and the sampling density is chosen as a compromise – too sparse a sampling smooths out the intended deformations, while too dense a sampling generates redundant data with no effect on print quality. The dependence of model quality on the manner of its discretisation is, moreover, known from the geometry of lattice structures: Savio, Meneghello and Concheri demonstrated that the application of subdivision surface schemes yields smooth models free of sharp edges, thereby reducing stress concentrations

[2] G. Vantyghem, T. Ooms, W. De Corte, *VoxelPrint: A Grasshopper plug-in for voxel-based numerical simulation of concrete printing*, "Automation in Construction" 2021, no. 122, art. 103469, https://doi.org/10.1016/j.autcon.2020.103469 (access: 10.09.2026).

[3] J. Jauk et al., *Termite: An Open-Source Grasshopper Plugin for Parametric Slicing in Architectural Clay 3D Printing*, "Journal of Manufacturing and Materials Processing" 2026, no. 10(4), art. 128, https://doi.org/10.3390/jmmp10040128 (access: 10.09.2026).

in the manufactured element.[4] The amplitude of the sinusoidal modulations is coupled to the layer number, which allows the deformations to build up and fade smoothly along the height of the object, while the diameter of the Pipe component corresponds to the actual width of the extruded filament, which in concrete printing reaches several centimetres, as against fractions of a millimetre in FDM technology.

3. FORM STUDIES AND PARAMETRIC VARIABILITY

The use of parametric design environments optimises the analytical process by eliminating the need to manually model individual iterations of the shape. Modifying the input variables – such as topological density, the global torsion vector of the solid or the amplitude of local deformations – results in a real-time reconfiguration of the entire model. This flexibility makes it possible to generate an extensive catalogue of morphological variants: from structures with a high degree of curvature to forms with minimised surface topography (Ill. 2–3). It should be emphasised that every generated iteration requires rigorous analysis in terms of statics and structural mechanics. Strict control of the centre-of-gravity vector and of the permissible overhang angles is an absolutely necessary condition. Owing to the absence of supporting formwork, the extruded concrete mix must exhibit sufficient initial load-bearing capacity to carry the loads of the upper layers of the structure on its own before the proper setting time is reached. Alongside the technical criteria, each variant was also assessed in terms of the quality of experience: whether the form sustains curiosity and guides the user's gaze and movement like a well-designed labyrinth – one that does not disorient visitors but builds tension, provides orientation and offers the satisfaction of discovery. From the engineering standpoint, freshly extruded concrete behaves as a yield-stress material: as long as the stresses do not exceed a critical value, the layer retains its shape, and thanks to thixotropy its stiffness increases with every minute at rest. Wolfs, Bos and Salet described this behaviour with a numerical model covering the first 90 minutes after a layer is deposited, based on a time-dependent Mohr–Coulomb criterion; they showed that the Young's modulus and cohesion of fresh concrete increase linearly with its age, whereas the Poisson's ratio and the internal friction angle remain constant over this period.[5] The very practice of coupling parametric design with optimisation and additive manufacturing was described methodologically by García-Domínguez, Claver and Sebastián, who built in Grasshopper a continuous flow of data between the model, the analysis and the selection of the best solution.[6]

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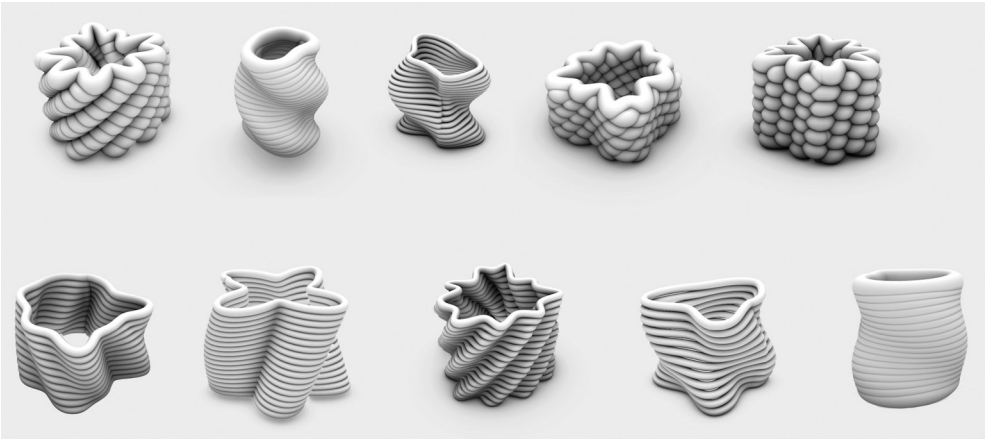
[4] G. Savio, R. Meneghello, G. Concheri, *Geometric modeling of lattice structures for additive manufacturing*, "Rapid Prototyping Journal" 2018, no. 24(2), pp. 351–360, https://doi.org/10.1108/RPJ-07-2016-0122 (access: 10.09.2026).

[5] R.J.M. Wolfs, F.P. Bos, T.A.M. Salet, *Early age mechanical behaviour of 3D printed concrete: Numerical modelling and experimental testing*, "Cement and Concrete Research" 2018, no. 106, pp. 103–116, https://doi.org/10.1016/j.cemconres.2018.02.001 (access: 10.09.2026).

[6] A. García-Domínguez, J. Claver, M.A. Sebastián, *Integration of Additive Manufacturing, Parametric Design, and Optimization of Parts Obtained by Fused Deposition Modeling (FDM). A Methodological Approach*, "Polymers" 2020, no. 12(9), art. 1993, https://doi.org/10.3390/polym12091993 (access: 10.09.2026).



Ill. 2. Variation of the planter body – error analysis. Visualisation in Rhinoceros. Source: authors' own work



Ill. 3. Variation of the planter body – range of the algorithm's capabilities. Visualisation in Rhinoceros. Source: authors' own work

4. SPECIFICATION OF MATERIAL MIXES

The successful materialisation of design intentions in the field of digital fabrication depends on the correlation between the architecture of the form and the physico-chemical parameters of the material. The key property of the mixes is their ability to consolidate immediately and to retain their shape directly after leaving the print head. On the basis of a literature analysis, three optimal material variants meeting these requirements were identified. The first is a standard mix based on Portland cement and fly ash, which constitutes the most common starting point, ensuring satisfactory consolidation and strength with the use of local binders. In situations where the risk of layer collapse under load to be minimised, a high-performance mix is used, in which the addition of silica fume, polypropylene fibres and viscosity modifiers drastically raises the yield stress and the resistance to shrinkage cracking. The third, ecological alternative is a cement-free geopolymer mix based on alkali-activated slag and fly

ash. Thanks to thixotropic additives (e.g. nanoclay), it shows great potential for facilitating the precise shaping of decorative forms. The material also has a sensory dimension: the raw, layered texture of the concrete, its coolness and weight engage touch on a par with sight, contributing to the emotional reception of the object – from calm to curiosity. In quantitative terms, printing mixes differ from ready-mixed concrete in their finer grading (aggregate usually up to a few millimetres), a lower water-to-binder ratio and carefully dosed admixtures: setting accelerators, plasticisers and thixotropic agents. An important parameter is the so-called open time, i.e. the window in which the material remains simultaneously pumpable and capable of bonding with the previous layer – exceeding it results in cold joints that weaken the monolithic character of the element. Geopolymer mixes additionally reduce the carbon footprint by replacing Portland clinker with industrial by-products such as blast-furnace slag and fly ash. The review by Rehman and Kim organises these relationships from the material side: it discusses the regulation of mix rheology by means of low-emission binders, waste aggregates, chemical admixtures and nano-additives, and documents the strength anisotropy of printed concrete, comparing it in the X, Y and Z directions.[7] The geopolymer direction is also being developed at PK Krakow University of Technology, where concrete–geopolymer hybrids incorporating fly ash and metakaolin have been successfully printed.[8]

5. PREPARATION FOR PRINTING – SLICING AND TEST PRINTS

The culmination of the computational design phase is the translation of the spatial geometry of the model into the precise language of numerical control (G-code). This process is carried out using specialised slicing software (e.g. Orca Slicer), in which the geometric algorithms are assigned specific execution parameters, such as the height and width of a single layer of the path, the feed rate of the extruder and the rules for any material retractions. In order to validate the kinematic assumptions before large-scale implementation, the rapid prototyping method is routinely applied. The use of FDM technology with PLA polymer enables early, safe and low-cost detection of path-planning errors and hidden geometric defects, thus preventing irreversible losses during the actual printing with a heavy concrete mix. Buswell and co-authors emphasise that print resolution – and hence the smallest reproducible detail – results from the cross-section of the extruded filament and the layer height, and is limited by the state of the fresh mix, the course of the path and the process parameters.[9] The universality of coupling the path preview with machine-code generation in Grasshopper is confirmed by applications at incomparably smaller scales – down to the fabrication of microfibrous tissue scaffolds.[10] The layer parameters

[7] A.U. Rehman, J.-H. Kim, *3D Concrete Printing: A Systematic Review of Rheology, Mix Designs, Mechanical, Microstructural, and Durability Characteristics*, "Materials" 2021, no. 14(14), art. 3800, https://doi.org/10.3390/ma14143800 (access: 10.09.2026).

[8] C. Ziejewska et al., *3D Printing of Concrete-Geopolymer Hybrids*, "Materials" 2022, no. 15(8), art. 2819, https://doi.org/10.3390/ma15082819 (access: 10.09.2026).

[9] R.A. Buswell et al., *3D printing using concrete extrusion: A roadmap for research*, "Cement and Concrete Research" 2018, no. 112, pp. 37–49, https://doi.org/10.1016/j.cemconres.2018.05.006 (access: 10.09.2026).

[10] K.L. O'Neill et al., *Visualising fibre path and generating G-code for melt electrowriting of tubular scaffolds using Grasshopper software*, "Virtual and Physical Prototyping" 2025, no. 20(1), art. e2466190, https://doi.org/10.1080/17452759.2025.2466190 (access: 10.09.2026).

also have perceptual consequences – they determine the rhythm of the visible layers, and thus the texture that the user will perceive visually and tactually under changing light throughout the day. The test prints are produced to scale, preserving the width-to-height ratio of the layer, so that they make it possible to assess in advance the behaviour of overhangs, the start and end points of the path, and the risk of the nozzle colliding with already printed material.

6. VISUALISATION OF THE FINAL OBJECTS

Direct evidence of the high applicability of the proposed research-and-design methodology is provided by the concepts of small architectural forms prepared for implementation in urbanised space. One example is an individualised planter with a highly complex topology resembling an openwork weave, located in a garden context (Ill. 4), and a more massive architectural element set in a park landscape (Ill. 5). The non-linear, organic morphology of the outer shells of both objects is tangible proof of how 3D printing technology can completely liberate form from the angular rigours imposed by traditional formwork systems. The photorealistic visualisations, which place the designs in their target environment, serve as an evaluation tool in consultations with investors. Placing the objects among greenery – in a garden and in a park – is not accidental: vegetation encourages one to pause and contemplate, and forms perceived differently by different users may become for some a place of rootedness and for others a lasting carrier of meanings and memory. At the implementation stage, operational issues remain important: the surfaces of the printed elements require impregnation to limit water absorption and facilitate cleaning, while the founding design and transport – given the mass of the precast elements – is planned already at the stage of the digital model, which provides precise data on the volume and centre of gravity of each object.



Ill. 4. Visualisation of a 3D-printed planter in a domestic garden. Source: authors' own work



Ill. 5. Visualisation of a 3D-printed small architectural form in a park space. Source: authors' own work

7. CONCLUSIONS

The process presented here – from the algorithmic definition in the Grasshopper environment, through the selection of mixes and slicing, to test prints and visualisations – shows that digital fabrication with concrete allows a controlled transition from an abstract idea to a stable physical object. At the same time, the study demonstrates that technology does not relieve the designer of the need to think about experience: printed forms are perceived in motion and with all the senses – with the eyes, through touch, with the whole body – and their geometry and texture evoke emotions without which architecture remains dead. Algorithmically generated small architectural forms can therefore be more than a technical curiosity: well integrated into public space, they become carriers of meaning and memory, and the design process becomes a philosophical practice in which the author remains a mediator between idea and reality. A natural direction for further research is the full-scale realisation of both objects together with strength testing of the printed samples and, in the longer term, the integration of reinforcement into the printing process and the development of tools that automatically account for technological constraints already at the level of the algorithmic definition.

References

[1] Buswell R.A. et al., *3D printing using concrete extrusion: A roadmap for research*, "Cement and Concrete Research" 2018, no. 112, pp. 37–49, https://doi.org/10.1016/j.cemconres.2018.05.006 (access: 10.09.2026).

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[3] García-Domínguez A., Claver J., Sebastián M.A., *Integration of Additive Manufacturing, Parametric Design, and Optimization of Parts Obtained by Fused Deposition Modeling (FDM). A Methodological Approach*, "Polymers" 2020, no. 12(9), art. 1993, https://doi.org/10.3390/polym12091993 (access: 10.09.2026).
[4] Jauk J. et al., *Termite: An Open-Source Grasshopper Plugin for Parametric Slicing in Architectural Clay 3D Printing*, "Journal of Manufacturing and Materials Processing" 2026, no. 10(4), art. 128, https://doi.org/10.3390/jmmp10040128 (access: 10.09.2026).
[5] O'Neill K.L. et al., *Visualising fibre path and generating G-code for melt electrowriting of tubular scaffolds using Grasshopper software*, "Virtual and Physical Prototyping" 2025, no. 20(1), art. e2466190, https://doi.org/10.1080/17452759.2025.2466190 (access: 10.09.2026).
[6] Rehman A.U., Kim J.-H., *3D Concrete Printing: A Systematic Review of Rheology, Mix Designs, Mechanical, Microstructural, and Durability Characteristics*, "Materials" 2021, no. 14(14), art. 3800, https://doi.org/10.3390/ma14143800 (access: 10.09.2026).
[7] Savio G., Meneghello R., Concheri G., *Geometric modeling of lattice structures for additive manufacturing*, "Rapid Prototyping Journal" 2018, no. 24(2), pp. 351–360, https://doi.org/10.1108/RPJ-07-2016-0122 (access: 10.09.2026).
[8] Vantyghem G., Ooms T., De Corte W., *VoxelPrint: A Grasshopper plug-in for voxel-based numerical simulation of concrete printing*, "Automation in Construction" 2021, no. 122, art. 103469, https://doi.org/10.1016/j.autcon.2020.103469 (access: 10.09.2026).
[9] Wolfs R.J.M., Bos F.P., Salet T.A.M., *Early age mechanical behaviour of 3D printed concrete: Numerical modelling and experimental testing*, "Cement and Concrete Research" 2018, no. 106, pp. 103–116, https://doi.org/10.1016/j.cemconres.2018.02.001 (access: 10.09.2026).
[10] Ziejewska C. et al., *3D Printing of Concrete-Geopolymer Hybrids*, "Materials" 2022, no. 15(8), art. 2819, https://doi.org/10.3390/ma15082819 (access: 10.09.2026).

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