ABSTRACT
The context of digital fabrication allows architects to reinvestigate material, process and the design decisions they entail to explore novel expression in architecture. This demands a new approach to design thinking, as well as the relevant tools to couple the form of artefacts with the process in which they are made.

This paper presents a customised computational design tool developed for exploring the novel design space of Concrete Extrusion 3D Printing (CE3DP), enabling a reinterpretation of the concrete column building typology. This tool allows the designer to access generative engines such as trigonometric functions and mesh subdivision through an intuitive graphical user interface.

Balancing process efficiency as understood by our industry with a strong design focus, we aim to articulate the unique architectural qualities inherent to CE3DP, energising much needed innovation in concrete technology.
INTRODUCTION
Since the invention of Portland cement in the 19th century and with continuous innovation in materials, processing, and structural applications, concrete has secured its place as the world’s most widely used engineered material (Ashby 2012). This is due to its versatility in applicative techniques, its low cost, and its comparatively high compressive strength. In the context of digital fabrication, where numerically controlled deposition allows unprecedented geometric freedom, architects are offered the chance to reinvent concrete building culture by exploring forms and processes deemed impractical or inconceivable before.

Brought under re-investigation through the lens of computational design, robotic fabrication and 3D printing, materials with a rich history such as concrete can embody new architectural expression. The relatively new field of Digital Concrete (Flatt and Wangler 2018) has enabled the investigation of processes that produce high-value building components, uniquely articulated in relation to their fabrication method. Amongst these processes, concrete extrusion 3D printing has been gaining a lot of attention from industry and research alike.

CE3DP is an additive manufacturing method where a fresh mortar is continuously pressed through the small aperture of a tool. In a numerically controlled process, the concrete filament is deposited in layers to materialise the digital model (Khoshnevis 2004). The significant advantage of this technique is that no formwork is used in the process of shaping the concrete, opening the door to more economic and environmentally lean fabrication. Amongst other additive manufacturing technologies, CE3DP reports fast printing speeds suitable for the creation of building elements and their large-scale implementation in architecture (Sika 2018). Within the broader research topic, this paper presents a computational modelling tool specifically developed for the design exploration of full-scale columns produced with CE3DP.

Columns have always served as archetypal elements of architecture that are at their simplest, vertical forms of support. Throughout the history of architecture, columns have appeared in classical to modern and contemporary architectural styles. As elements integral to modern structural design, they have often been associated with expressions of harmony, balance, and proportion. These characteristics are being contextualised in the emergent field of digital fabrication technologies. Engaging with material in a novel and informed manner enables a re-examination of the role of ornament and differentiation in architectural design.

3D PRINTED COLUMNS
Both as architectural and structural building components, columns are characterised by their vertical height and a comparatively reduced cross-sectional area. The versatility of 3D printing allows for complex geometries to be fabricated in an orientation matching that of the element’s final use. This affordances of the fabrication process are identified and utilised early on in the design process. For our application, correct material deposition depends on a relatively high horizontal processing speed, far superior to other 3D printing processes. This translates into a very fast vertical building rate, reflected in the rapid increase of strength build-up in the concrete necessary to support subsequent layers. From a structural point of view, column geometries have a high risk of failing through buckling during fabrication due to the horizontal cross-section area to height ratio. Referring to the mechanisms responsible for structuration associated with layered extrusion in relation to buckling (Reiter et al. 2018; Wolfs et al. 2018), the strength build-up has to rely on the formation of hydration products in the printed concrete. Given the relatively fast succession of layers, the process must use admixture triggered hydration. This technique is, however, not commonly reported as a successful fabrication strategy because it involves some processing drawbacks. The most important challenges reported include difficult pumpability and extrudability given the high-viscosity of the material and low ability of the mortar to gain sufficient strength for the required printing height. Our system was developed with the goal of activating the mortar immediately after leaving the extruder tool using a set-on-demand (Wangler et al. 2016) material processing strategy.

In spite of the technical challenges, we can name several digital fabrication methods where bespoke concrete columns have been successfully produced. The first example is the research project Smart Dynamic Casting at ETH Zurich as shown in Figure 2a (Lloret et al. 2017).
Here, a numerically controlled formwork is translated to replicate the traditional slip-forming technique at a scale relevant to a column typology. Set-on-demand activated mortar continuously fills the slip formwork to create bespoke vertical elements. The obvious advantages of such a technique is the possibility to integrate reinforcement and to achieve surface finishing similar to that of cast concrete. Nevertheless, its shortcoming is the limited design space of curvilinear translations that can be produced with a particular formwork section. Additionally slip-forming is a process that works only for prefabrication scenarios due to its sensitivity to material variations (Wangler et al. 2016).

An example of research strongly focused on design but disregarding some essential structural properties of the printed material is Fossilized from The Bartlett School of Architecture as shown in Figure 2b (Amalgamma 2015). Here, overhangs of the fresh concrete are supported during fabrication by additional layers of salt. This exemplifies a hybrid fabrication solution that combines layered extrusion with particle bed 3D printing (Lowke et al. 2018). Another example is the 3D printed formwork of a truss pillar from XtreeE as shown in Figure 2c (Gaudilliére et al. 2019), which is a successful implementation of a 3D printed structural element in an architectural project. The permanent formwork of the truss pillar is printed in segments, stacked vertically, and subsequently filled with ultra-high-performance concrete. This aligns the project to French building code standards. After curing, the support material between the openings of the truss is removed and the whole column is plastered. In this case, the limitations of layered extrusion such as interfaces between printed components or cutouts of the truss openings are overcome by manual post-processing. The Liquid Rock installation, as shown in Figure 2d (Efthimiou and Grasser 2018), shows great advancement in the processing strategy, geometric freedom, and print-path design achievable with CE3DP. Finally, another important example uses implicit modelling to generate a robotic print-path (Bhooshan 2019). The project investigates a previously unexplored design space by printing with concrete as well as simulating material behavior and printability. Both the Liquid Rock and implicit modelling prototypes are fabricated with the industry-developed process BauMinator (Baumit 2019).

Customisation and material optimisation are goals that all digital concrete projects identify as essential. Extending these avenues of research, this paper showcases the potential of CE3DP to produce functional, hollow structures directly-fabricated in concrete at high resolution. The result is the successful 3D printing of articulated building components. The proposed design processes require a novel approach to design thinking as well as new computational design tools. CE3DP is not seen as a fabrication method that replaces well established industrial processes, nor one that borrows design vocabulary and constraints from said processes. We explore computational design spaces and robotic fabrication solution spaces that enable us to contribute to the formal and technical repertoire of concrete columns.

**DESIGN METHODS**

The scope of the proposed digital design tool is to transform a generic computational mesh of a given height and diameter into a 3D-printable column. This tool relies on an intuitive Graphical User Interface (GUI) that offers direct...
visual and numerical feedback to its user, thus enabling fast design iterations. The chosen generative engines, namely trigonometric functions and mesh subdivision, are just two possible ways to manipulate the initial computational mesh. What follows is a detailed description of how the design tool was developed.

**Column App**

The polygonal mesh offered the advantage of an efficient data structure that enabled multi-scalar malleability and the storage of relevant information for extrusion-based fabrication, such as edge lengths and vertical inclinations. For this purpose, we used the MOLA (Dillenburger 2019) open-source mesh library built on an edge-based data structure.

Moreover, the computational design tool was developed as software-independent as possible in pure Python code. For full usability during the design phase, all relevant mesh manipulation and analysis techniques, as well as extensive visualisation and export functionalities were merged into a single software Applet using the Python Processing framework (Feinberg 2014), with comprehensive GUI. Consequently, this allowed for the efficient testing and evaluation of numerous design iterations. The following section describes the two computational engines available in the app: the trigonometric function engine and mesh subdivision engine.

**Trigonometric Function Engine**

Inside the computational design tool, the trigonometric function engine involves the displacement of points according to a hierarchy of trigonometric functions (Figures 3-4). The data structure is a 2D array of points consisting of positions within a curve layer, with the layers making up the full height of a column. Combined into a continuous spiral, the manipulated points represent the robotic position planes that are sent directly to the robot controller.

An example of a concrete printed building element using similar mathematical functions is the Sinusoidal Wall by XTreeE (XtreeE 2016). As demonstrated in this project, undulating displacements of points according to trigonometric functions is integral to the creation of sinuous print-paths, making the resulting robotic movement ideal for continuous concrete extrusion printing. Sharp turns that introduce robotic speed fluctuations can negatively affect print quality. Using the wave motion path, these discrepancies were minimised.

**Mesh Subdivision Engine**

Subdivision rules: [a] input quad-mesh face; [b] tapered or extrude_to_point; [c] grid; [d] longitudinal tapered, or extrude_to_line; [e] extrude

Vertex count increase using mesh subdivision: [a] low resolution mesh input; [b] subdivided mesh; [c] smooth mesh

5 Modular App architecture developed in Python Processing, the resulting OBJ geometry file can be communicated for generating the fabrication data
For the column design, the computational tool allowed the control of frequencies, amplitudes, and phases of iterative trigonometric functions to generate columns with varying levels of geometric complexity. According to function values, points between layers were displaced incrementally with the effect of accentuating features along the height of the column to distinguish the capital or base. Moreover, points within a layer were displaced to create tighter articulations or were expressed with variable layer heights.

The above-mentioned data structure made it simple to analyse curvatures within a layer and overhangs between layers, along with the ability to incorporate material, geometric, and fabrication feedback from prototyping tests as constraints into the design applet itself. Overhang, curvature, and variable layer height domains were defined as parameter limits in the design tool to inform feasible designs and output the associated geometric information related to the robotic print-path.

Mesh Subdivision Engine

Mesh subdivision is a procedural design process that alters the data structure of a given mesh by increasing the number of vertices and faces. This computational design process is extensively explored in the mesh grammars of Hansmeyer (Hansmeyer 2010) by the subsequent subdivision routines inspired by Catmull_Clark (Catmull and Clark 1978) and Doo Sabin. The transformation is performed by a mapping function that associates rules to specific types of mesh faces. A notable quality of mesh subdivision is its extensive morphologic differentiation potential, as exemplified in Digital Grotesque (Dillenburger and Hansmeyer 2014).

For the column design, initial faces of an input quad-mesh are grouped based on their height into ‘base’, ‘shaft’, and ‘capital’. Next, generic subdivision rules like ‘grid’, ‘tapered’, ‘longitudinal tapered’, and ‘extrude’ are applied iteratively to generate the new column geometry (Figure 5). It is worth mentioning that the rules in [d] and [e], ‘longitudinal tapered’ and ‘extrude’, have to be applied with a certain orientation and can break the manifold structure of a mesh. Here, the horizontal and almost horizontal faces should be excluded from the subdivided iteration, because these faces are impossible to print, and may create discontinuities in the print-path when sliced. Interesting design features and perceived depth can be introduced with the tapering or extrude_to_point rules in [b], where bridging porosities in the subdivision column can be created. Subdivision rules which create edge vertices, like [c] and [d], need to be considered globally when applied to a mesh. In a first step, a classification of edges is performed. The filtered edges will either get an additional vertex or be subject to a method of triangulation. The latter avoids situations in which the manifold structure of the mesh is broken. After successive iterations of the subdivision rules, a Catmull_Clark mesh smoothing algorithm, accessed from the same open-source library, adds a further degree of refinement to the mesh.

Unlike the mesh subdivision (Figure 6), the trigonometric function method has all vertices declared from the mesh initialisation (Figure 4). The topology and structure of the mesh do not change during the translation process. The different hierarchies, scales, and detailing levels are reached by different frequencies applied iteratively. Mesh subdivision methods are not bound to keeping the structure and topology of the mesh intact. The resolution at which it is computed depends on the resolution allowed by the fabrication technique, which in the case of concrete extrusion will be described in the following sections.

Column App

To allow for flexible integration of the mesh manipulation engines and custom algorithmic routines, a modular software applet integrating all generative design modules was developed. The main Applet wraps around mesh manipulation engines, display, export and GUI modules (Figure 7). Furthermore, the implemented OBJ file exporter provides the exchange of generated geometries with complementary

8 Interface of the generative column design tool with central mesh display; (left) visualisation, slicing, and export functions; (right) mesh manipulation parameters

9 Analytical information from the App: [a] group type; [b] face area in cm²; [c] shaded preview; [d] face perimeter in cm; [e] vertical angle in radians
software environments for further toolpath processing, custom to the extrusion technique.

The developed GUI is structured into a control panel on the left containing visualisation options, slicing analysis, and export functions, a control panel on the right for mesh manipulation-specific parameters, as well as the central 3D representation of the geometry (Figure 8). The various visualisation modes that can be displayed on the central viewer are chosen from a drop-down menu containing analytical information for the generated mesh, such as face group type, curvature, face area, perimeter, compactness, and vertical angles between faces (Figure 9). The slicing preview can be controlled and displayed with a horizontal plane cutting the column geometry. Moreover, the resulting intersection curves between cutting plane and generated mesh are illustrated in a 2D viewer.

Consequently, various mesh geometries could be explored and validated numerically and visually with the built-in set of analysis routines. Empirical data from conducted experiments during the prototyping phase of the project, such as the inclination and size of overhangs, further informed the tool and led to a robust and reliable design explorer with realistic results regarding printability.

**DESIGN METHODS**

The CE3DP fabrication setup

The layered extrusion concrete printing process utilised in this research involves an initial mix of a very large batch of mortar (sufficient to build one entire column), retarded with sucrose to give an open time of six to eight hours. The mix uses calcareous crushed sand with a maximum grain size of 2 mm, ordinary Portland cement (CEM I 52.5R) at a water to cement ratio of 0.4, 8% substitution of microsilica, and 15% substitution of limestone powder. A PCE superplasticizer (BASF Glenium ACE 30) is dosed at 1% by weight of binder, and a special viscosity modifying additive (supplied by Akzo Nobel AG) is dosed to give a high initial yield stress at rest while still facilitating pumping.

A Swingline progressive cavity mortar pump delivers the material to the nozzle end effector on the ABB robotic arm, where it is then dosed with an activator (a calcium aluminate cement paste) in a specially designed mixing reactor. The activator is dosed via a membrane pump at a dosage of approximately 2% substitution of the ordinary Portland cement fraction (Figure 10). From the mixing reactor, the mortar flows to the extrusion point, where it is finally deposited.

This innovative material and processing system enabled the fast build-up of vertical concrete structures without interruption. It allowed high printing resolution of varied layer heights (from 12 mm down to as little as 4 mm), fast printing speeds between 200 - 450 mm/s, and sufficient strength buildup of the material, enabling the realisation of bespoke concrete columns at a vertical building rate of 3 m/h.
Segmented Columns Using Trigonometric Functions

Contrary to traditional 3D printing approaches that take the input of a predetermined form which is later horizontally sliced, the trigonometric function displaces points that are part of the print-path design itself. In the case of CE3DP, which has relatively large layer heights in the range of 4-12 mm, horizontal slicing would redefine a representation of the design in steps of layers. On the contrary, by varying layer height, vertical geometric control over design space can be improved. Because the robot is able to move precisely along a designed curve, the potential for 3D manipulation and expression can be explored. The direct coupling of design features with fabrication parameters along a print-path makes this design approach highly suitable for CE3DP.

The experiment in Figure 11 illustrates layer height calibration at constant material flow-rate and variable print-speed (speed of robot movement). It is shown that print-speed must be adjusted to local layer height (Figure 11c and 11d). If print-speed is too high, insufficient material is placed for the following layers to adhere to (Figure 11a), while if it is too low, too much material is placed resulting in uncontrolled surface artefacts (Figure 11b). Experiment 11d accentuates the transition between thick and thin layers. In 11d, even if the print-speed corresponds to the target layer-width and layer-height, the object fails through buckling because the proportion between the height at the peaks of the shape and wall-thickness is not structurally sound. Even if similar design variations of the layer height were previously reported (Efthimiou and Grasser 2018), the presented experiment utilises an integrated design approach for layer variability as a visible design feature. This is done to break the dominant horizontal aesthetic of extruded layers often criticised when judging outcomes of CE3DP.

During design it became obvious that an internal core would offer extra structural support during printing. However, at high print-speed the sharp angles of the interior core proved problematic (Figure 12b). At these sharp angles, because of motion optimisation features of the robot controller, the robotic motion resulted in being jagged and slower than the target velocity. This led to excessive and poorly controlled material placement. As a result, an interwoven self-intersecting path was created (Figure 12c), enabling faster robotic motion at the transition from outer shell to the inner core. The reason why sharp corners are difficult to print is because the robot cannot change the direction of movement and simultaneously keep the printing speed constant. This design enabled printing at relatively high speeds of up to 450 mm/s. A 1.2 m segment using variable layer height between 5 mm and 12 mm was successfully fabricated, as shown in Figure 11. For the short print time of 20 minutes, the smoothness of the print-path was essential to ensure that the robot reached the target speed, which continuously varied between 300 and 450 mm/s. This allowed a consistently high quality of printing as well as fast vertical build-up (approximately 3m/h or 10s per layer), which as mentioned before, is essential for the creation of large-scale components.
Printing a column with variable layer heights allows improved control over the design of the resulting printed surface (Figure 15a), usually dominated by a horizontal layered aesthetic. Another benefit is that in the assembly of larger-scale structures, the aesthetics of interfaces between printed parts can be enhanced. Here variable layer heights allow the creation of non-planar, 3D interlocking seams (Figure 11c) that emphasize the design language rather than distract from it.

Mesh Subdivision Columns

The column generated using the previously described Mesh Subdivision Engine is shown in Figure 14. Its geometry explores features impossible to produce in concrete with any formwork-based fabrication method, such as an intricate internal structure or closed and opened porosities. This is because the formwork needed would need to be suspended in midair during casting and some formwork would be lost during production. Geometric features of subdivided meshes, such as self-intersecting meshes, result in self-intersecting print-paths that prove beneficial for the fabrication process as they improve shape stability. Self-intersecting print-paths create interwoven material artefacts and extend design space with porosities that are created through overhangs that meet in mid-air (Figure 15b). Unlike the previous column example, where the core had to be added as a distinct geometry, the subdivided mesh generates its own interior folds that create an integrated vertical core with multiple chambers. In this example, a slicer was used for the print file generation due to the complexity of the design.

Nevertheless, geometric complexity has some drawbacks. In order to print the intricate print-path resulting from the mesh subdivision, the printing speed had to be reduced considerably, down to 200 mm/s from the speeds described in the previous section. This increased the total print-time of the 2 meter tall column to 2 hours. Additionally, for concrete extrusion, not all designed geometries are immediately printable. Even though slicer input does not require a closed mesh as in the majority of 3D printing methods, there are specific limitations regarding overhangs, printing resolution, and sharp turns of the print-path (Figure 12). Furthermore, a very intricate print-path that describes a large object sliced at high resolution creates a large data file. At the time of the research, this proved to be a limiting fabrication factor influencing the minimum print resolution which became 6 mm in layer height, instead of the 4 mm supported by the printing tool.

Given the unique fabrication possibilities of CE3DP, conventional design tools prove insufficient for the full exploration of the design potential inherent to this technology. The unique design features pursued above demonstrate the benefit of custom computational design tools that can complement an innovative fabrication process. Developed to produce print-paths that are both uniquely possible with CE3DP and beneficial for the fabrication process itself, the presented research advances computational design tools for digital fabrication with concrete.
OUTLOOK
This research integrates a series of key aspects shaping the current discourse on digital concrete. Out of the synergy between design methods and fabrication methods, a series of successful full-scale demonstrators were realised. Aside from generating large scale structural building components, the research has also opened several new avenues of research and optimisation opportunities. Regarding future possible optimisations of the column app, we identify the need to develop a more integrated design tool that embeds advantages given by both trigonometric functions and mesh subdivision engines. New methods of digital design—such as procedural mirroring, Fourier transform operations, and volumetric modelling (Bernhard 2018)—can make a valuable contribution to our toolkit. Our typological repertoire will benefit from a design tool that enables the design of multiple structural typologies, such as slabs and beams.

CONCLUSION
Presently, digital fabrication with concrete is gaining a lot of attention from the research community, hence the question of how to design for emerging digital fabrication processes requires a sharper focus from designers and architects alike. CE3DP shows significant opportunities for the creation of bespoke architectural elements and novel material expression. New fabrication methods suggest new approaches to design thinking that are embodied in custom computational tools. The presented computational workflow was developed as an educational tool and is currently being used in the context of the Master of Advanced Studies in Architecture and Digital Fabrication at ETH Zurich.

This paper proposes an approach to concrete column design that balances process efficiency with a strong design focus, aiming to articulate the unique technological potentials and architectural qualities inherent to CE3DP.

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REFERENCES
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