Unprintable Forms

Complexity as a Robustness Factor for Robotic Fabrication and
3DCP Constraints through Error Elimination and Reinsertion

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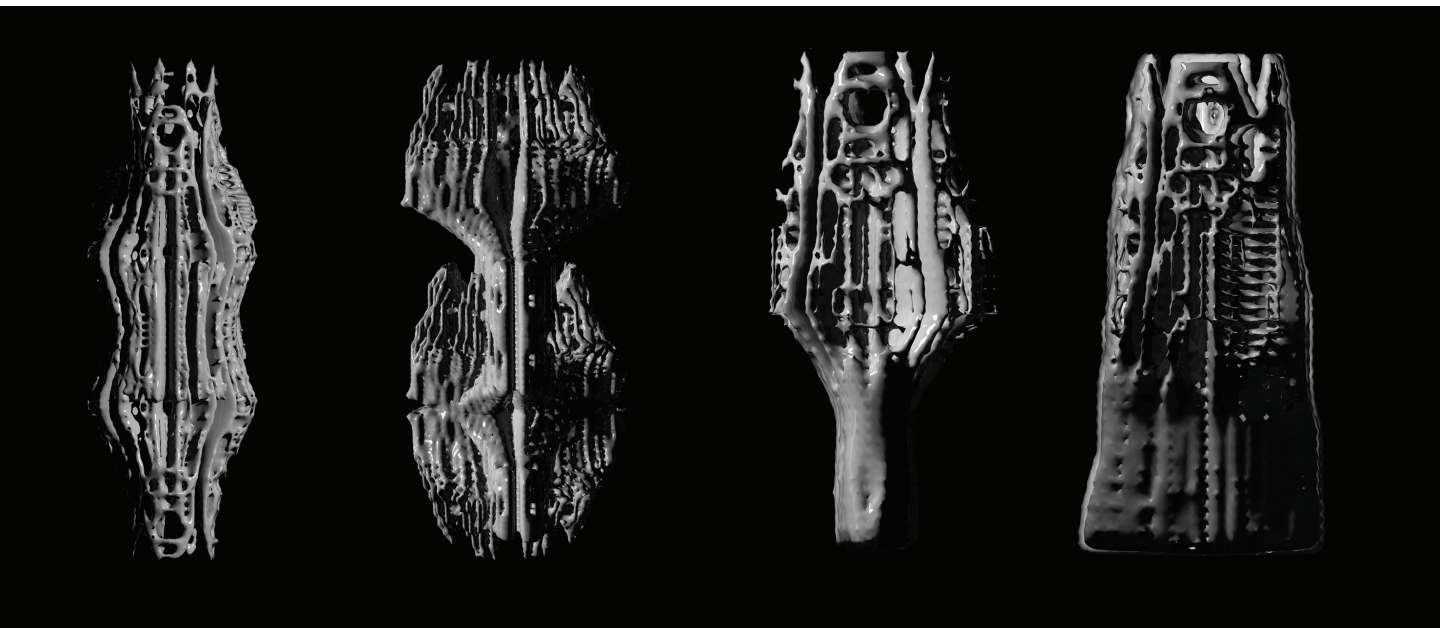
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ABSTRACT

This paper presents a 3D Concrete Printing (3DCP) experiment at the full scale of virtual-
architectural bodies developed through a computational technique based on the use of
Cellular Automata (CA). The theoretical concept behind this technique is the decoding of
errors in form generation and the invention of a process that would recreate the errors as
a response to optimization (Adilenidou 2015). The generative design process established
a family of structural and formal elements whose proliferation is guided through sets of
differential grids (multi-grids) leading to the build-up of large span structures and edifices,
for example, a cathedral. This tooling system is capable of producing, with specific inputs,
a large number of outcomes in different scales. However, the resulting virtual surfaces
could be considered as "unprintable" either due to their need of extra support or due to the
presence of many cavities in the surface topology. The above characteristics could be cate-
gorized as errors, malfunctions, or undesired details in the geometry of a form that would
need to be eliminated to prepare it for printing.

This research project attempts to transform these "fabrication imprecisions" through
new 3DCP techniques into factors of robustness of the resulting structure. The process
includes the elimination of the detail / "errors" of the surface and their later reinsertion
as structural folds that would strengthen the assembly. Through this process, the tangible
outputs achieved fulfill design and functional requirements without compromising their
structural integrity due to the manufacturing constraints.

1   Vertical Series _ Mesh outputs
    generated with CA systems

INTRODUCTION

There has been significant development and achievements in integrating 3D Concrete Printing (3DCP) within the construction industry (Bos et al. 2016). However, most of these developments still rely heavily on manual interventions and lack of integration of the various activities and operation stages from design to manufacturing phase. Particularly, in building and infrastructure scale, 3DCP is characterized by a lack of variation and customization. However, the design complexity produced via computation and material explorations is continuously increasing while there is an augmented demand in the need of convolutedness, variation, and flexibility for constructing an uncertain future.

Through Additive Manufacturing (AM) any innovation and intricacy in design that can be perceived virtually can be easily translated in a tangible form, with a high degree of material optimization, creating additional opportunity for introducing the applications of robotics and automation in construction. Intense research is being carried out for the implementation of AM in different fields; however, application of 3D printing in the concrete construction industry still faces limitations, such as scale in relation to material properties and dynamics, cantilevers, and need of support. Although, complexity acts as an extra problematic to the above limitations, we want to propose it as a robustness factor augmenting the structural efficiency.

The paper presents a series of 3DCP experiments of forms considered unprintable due to their low printing feasibility and the detail in excess that would produce fabrication failures/errors. Construction inefficiencies are studied in relation to structural integrity and optimization (Figure 2), producing new solution tools through Grasshopper and Rhinocheros. The Eindhoven University of Technology (TU/e) was selected for the experiments due to their large-scale printing setup that would enable the production of complex forms as structural and building elements.

One of the most important steps in fabrication research over the last decades is the build-up of a direct link between the design geometry and the fabricated object. Forms had to be generated with a specific approach to optimization, through a "clever use of geometry rather than design freedom" (Gosselin et al. 2016). Still, no matter how significant this step was in search of novel and robust fabrication techniques, it ended up in design experimentation being forgotten or sidelined in fabrication discourse. The previous utopian structures, even these of early and later computation, were not in line with the current manufacture experimentation with very few exceptions.
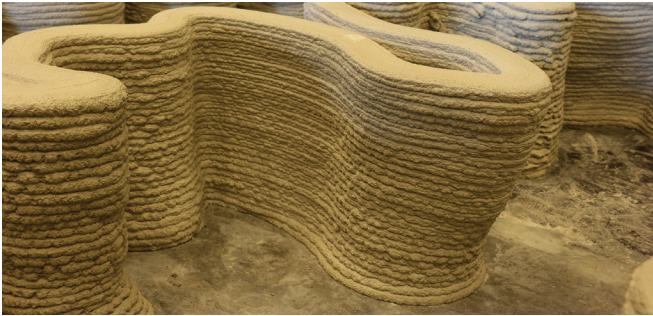

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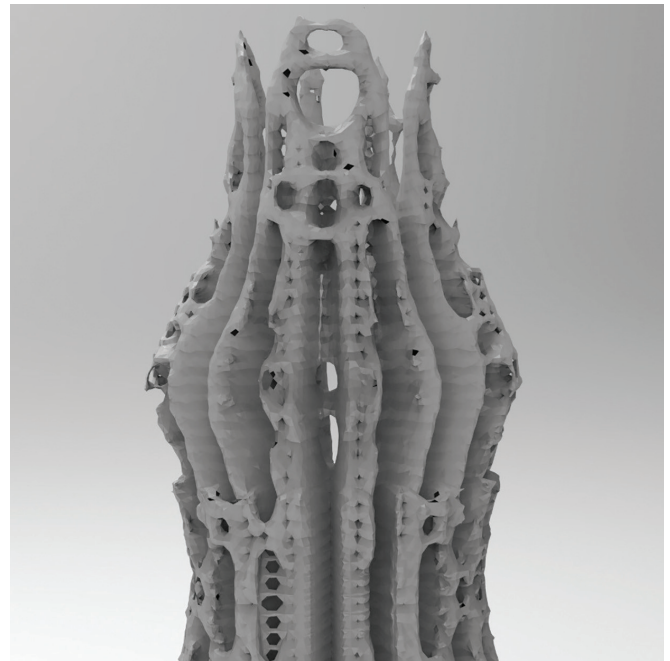
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2   Final 3D printed structure   3   Selected meåsh for the 3DCP

Earlier 3DCP Research

Concrete, among other materials, due to its different curing phases and its viscosity levels, has been a popular material for 3D printing at full scale, a technique that has always been associated with computational design and form freedom. There has been a great number of 3DCP experiments in larger and smaller scales—from the rigid engineering of walls and shells at full-scale of Contour Crafting from Prof. Khoshnevis group (Khoshnevis et al. 2004) to the sculpting qualities of the collaborative project between Anish Kapoor and Factum Arte on cement printing, focusing on randomness and material properties (Schaffer et al. 2015).

Contour Crafting (CC) by Khoshnevis et al. is a layering technique for large-scale 3D printing (in use since 2000), using end-effectors like traditional tools (e.g., trowels), adjusted to the extruder in order to achieve optimized surfaces of extrusion and avoiding the traditional casting on wooden formwork (Khoshnevis and Bekey 2002). The CC technique was limited to vertical stacking of 2.5D (Gosselin et al. 2016) or vault fabrication through inclined slicing (Khoshnevis et al. 2006).

On the other hand, Concrete Printing by Loughborough University uses a gantry system, and the process involves lab-based production and supports for the printed structure (Lim et al. 2012). Smaller extrusion thickness combined with higher performance concrete for 3D structures, but the supports increase the material cost and the system efficiency (Gosselin et al. 2016). XTreeE invented a system for

3D Printing without the use of supports through a "tangential continuity method," thereby "avoiding the geometrical gaps between two layers" and using different thickness layers (Gosselin et al. 2016), enabling the construction of structural elements or formworks for molding that cannot be produced in any other way.

All of the above processes follow the extrusion-based printing technique, and they lack complexity and detail intensity at least in the larger scale. On the other hand, the extremely detailed and intricate Digital Grotesque by Benjamin Dillenburger and Michael Hansmeyer (Dillenburger and Hansmeyer 2014) uses a different method allowing the detail intensity—one of sand Binder Jetting 3D printing. Enrico Dini's D-Shape technology uses a Binder Jetting method at an architectural scale by depositing full layers of aggregates on top of which a layer of "ink binder" that is applied locally binds the aggregates into the architectural structure (Dini, d-shape.com). ETH Digital Building Technologies have recently worked with the idea of a formwork printed with sand Binderjet (with some additional FDM parts) and used as a mold into which concrete would be sprayed to create filler surfaces, while a ribbed load bearing structure would be formed with casting on a plywood laser-cut panels' formwork (Meibodi et al. 2018).

Objectives - Hypothesis

All the above technologies and experiments—except maybe the Digital Grotesque by Dillenburger and Hansmeyer, which includes high intricacy, without structural properties however—used designs driven by certain fabrication

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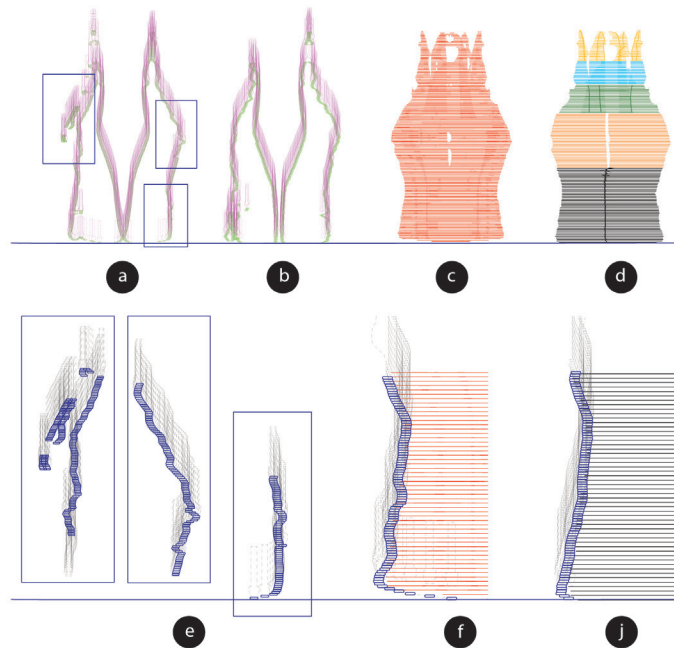
4   Cavities formation by the movement of spikes – spikes touch – resulting volume seems unbroken

5   3D Print – Detail – print of maximum height 25 layers

6   Final 3DCP Structure

7   (a, b) Section on toolpaths before and after adjustments; (c, d) Contours before and after adjustements; (e) Sections of deposited material on toolpaths in different heights before adjustments; (f) Sections of deposited material on toolpaths in bottom part, before adjustements; (j) Sections of deposited material on toolpaths in bottom part, after adjustements

rules. The forms follow printing feasibility built upon an understanding between geometry and fabrication; here, physics constraints, and therefore, "building feasibility can be transformed into a geometric reasoning problem" (Khoshnevis et al. 2006). However, this drove the design process on a specific direction of surface optimization, through schemes that were not only adjusted but also generated originally according to printing limitations without integrating a certain category of fabricating experiments for designs that obey different rules, for example aesthetics, intricacy euphoria, and convolution.

In the project presented, the original design was created independently from a fabrication technique following a theoretical concept and a design toolbox that could be implemented in different scales and objects. By default, the original geometry was not 3D printable in large scale and without support, as sculpting elements and complexity—e.g. cavities in the surface, sharp curvature, and intense cantilevers—produced areas that would fail to be printed. Detail was therefore an error for elimination as the process required smooth surfaces and minimum/zero cavities. The identified errors/details were eliminated, followed by a process of detail reinsertion through a novel path generation technique. The error reinsertion ended up as an important robustness factor (Figures 2, 6).

Furthermore, the extrusion-based technique can be used to create a permanent formwork that will not be removed after molding completion. Instead, it can serve as the external surface of a self-supporting structure and as

a mold to cast concrete, turning all the final elements to structure. The concept of mortar formwork was used as well by Khoshnevis team in wall experiments to replace wooden formwork (Khoshnevis 2006), as well as by Gosselin et al. (2016). Some geometries, due to complex topology, need support to be 3D printed so as not to collapse, which is what happened to our case initially (Figure 12). However, if they are finally constructed, they become "very stable load bearing structures" (Khoshnevis et al. 2006). Formal stability of the freshly printed concrete surfaces in cantilever structures (Kazemian et al. 2017) and deformation tolerance were tested, reinvented, and embedded. Folds became factors of structural robustness and efficiency.

Consequently, the objectives of the research presented were the following:

• Constructing unprintable surfaces / starting from a complex design form that is not generated according to fabrication limitations
• Turning candidate failure elements to robustness features, closing the gap between unprintable and printable designs, between design freedom and control
• Prototyping a process instead of a project for further custom-designed surfaces within the same design family
• Reintroducing complexity and sculpting as building elements in large-scale fabrication
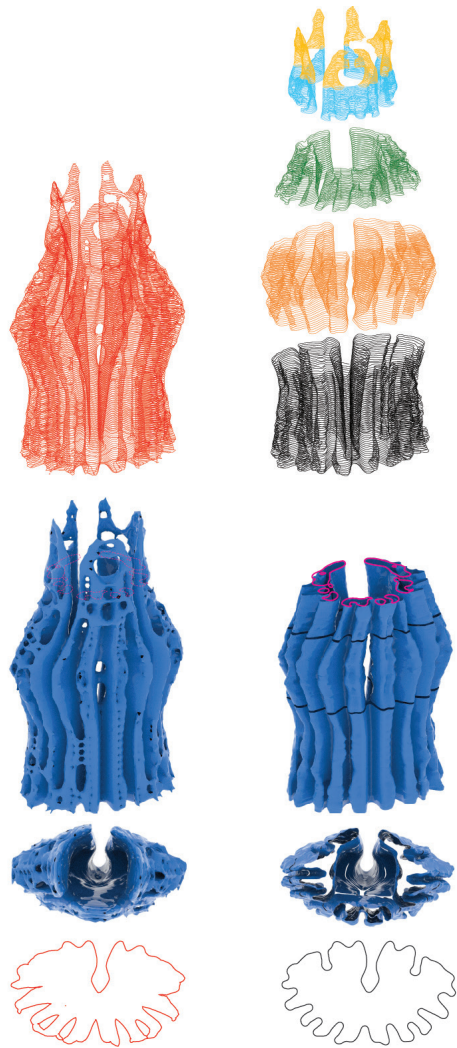
8 Contours and meshes before and after adjustments

DESIGN METHODOLOGY
OF THE ORIGINAL FORMS

According to Carroll's "embryo geography" (Carroll 2007), the perfect grid of the embryo structure develops during growth to an imperfect full body, where various matter depositions on different grid points lead to a formal variation and potential errors. Inspired by this evolutionary concept, some original design explorations investigate the accumulation of matter and the generation of form originating from uniform grids and equally distributed information. Sharing a similar concept based on grids and neighboring conditions, Cellular Automata (CA) structures are explored for the growth of series of architectural bodies.

CA structures are developed and proliferated in generations around rotational grids (Adilenidou 2015). The algorithm follows Stephen Wolfram's labyrinth code 747

(Wolfram 2002). The grid is created by the edit points of a polar array of curves. CA are distributed in the generations of the form as new points resulting in a point cloud that will be meshed into a mass (Adilenidou 2015).

The experiments were divided into three parts. The first series of design tests resulted in vertical linear elements that could be compared and related to structural elements such as columns and load-bearing walls (Figure 1). The second set of design experiments considered the spatial arrangement, whereby the initial polar array grid was replaced by a multigrid of more polar arrays with different centers, sizes, and overlaps, referencing gothic architecture and rotational arrays of ceiling nerves. While examining errors in form generation, the seemingly perfect typology of Cathedral was suitable to address issues such as symmetry mutations or similar errors found in organic growth. In the last set of experiments, Boolean operations among the ceiling-ruled surfaces of Gaudí's Sagrada Familia became an inspiration for the continuation of the methodology to generate surface subdivision and create detail intensity and complex distribution of light, shadow, and air into the building—through an arrangement of perforation and surface sculpting. The same methodology worked as a toolbox of commands, orchestrating different scales. The end product was a taxonomy of digital bodies of high complexity that varied in relation to symmetry axis, number of axis, direction of growth, resolution, subdivision and subdivision axis, and arrangement of local deviations, such as distribution of cavity patterns dissimilarities around the body (Adilenidou 2015).

The 3DCP experiments started with elements from the linear vertical series, the simplest of the design family (Figure 3).

METHODS: GENERATIVE DESIGN
AND 3D PRINTING TRANSLATION

The selected architectural body was a column, of which a part of 1.80m height and 1.50m width was isolated for printing (Figure 3). The structure and proliferation process of CA through the stacking of generations allowed for a direct relation of the generative design to the layered 3D printing procedure. However, in this first experiment, the design had already been completed before the fabrication research and selection of the 3DCP setup. Still, the algorithm allowed the integration of the machine's settings and limitations of the chosen framework—such as maximum cantilever distances between layers—in the design process and the distribution of points. Within this fabrication stage, focusing on the specific system set-up at TU/e and the conversion of the highly complex initial geometries into

printable ones, we encountered a series of technical limitations and developed printing strategies to subjugate them, as follows.

Translation of a Polygon Mesh into a NURBS Surface

To attain flexibility and adaptability of the toolpaths with readjustment on demand, it was essential to convert the original mesh model into a NURBS surface that could be contoured in multiple ways, providing different toolpaths for various scales. The mesh was contoured in Rhino, and the contours, after several adjustments discussed later in this section, were lofted to create a surface that would serve as the input for the Grasshopper script, recontouring according to scale and height of deposited layer and building the G-code. Another Grasshopper script aligned all initial control points of the input contours and the output toolpaths, so that the visible printing pattern would be uniform, eliminating any possibility of the robot traversing the form while resetting each new position in the following layer (Figure 11c).

Resolution and Smoothness of Curvature

The intricacy of the mesh to be printed was extensively higher than the capacity the printer could handle due limitations in robot kinematics, which is discussed more in detail by Ahmed et al. (2016). Hence, at the first stage the original contours were rebuilt in Rhino to remove automatically the excess of convolution by eliminating a first layer of undesired, disruptive angles and smoothen the movement of the robot in the resulting toolpaths (Figure 8).

Limitations in the Curvature of the Printed Layers Due to Nozzle Width

The size of the nozzle and the thickness of material printed required adjustments to the curvature of the resulting fillets in the folds to ensure a robust movement and a successful outcome. The filet radius at the angles of extreme curvature was increased in Grasshopper to equal or more than the width of the printed layers to avoid the twisting of filament in the inner corners (Figures 10, 11).

Cantilever Constraints

One of the limitations of 3DCP is the maturity and setting time of concrete during the wet phase of printing. Time gap between layers when increased can result in lower bond strength; however, when reduced the time gap "may cause severe deformations in freshly printed concrete" (Kazemian et al. 2017). To account for this factor, angle inclination during the vertical stacking of layers was limited in height to avoid collapse in the stacked material due to its self-weight (Bos et al. 2016). For the initial printing test, the cantilever distance between two consecutive layers

was limited not to exceed 20% of the overall width of the printed layer/thickness of printing nozzle, ammounting to 3 cm. All tooling paths were recalculated in Grasshopper in relation to their previous layers so that the cantilever would not exceed 6 mm (Figure 5). A more substantial inclination angle was achieved by adding an accelerator to the concrete mix, which drastically reduced the setting time during the wet phase and improved the stacking capability and stability of the concrete layers (Figure 12). Pieces were printed with maximum height of 25 layers (Figure 5). The surface was divided into parts that were fabricated separately in different positions on the printing bed and left to cure (Figure 9).
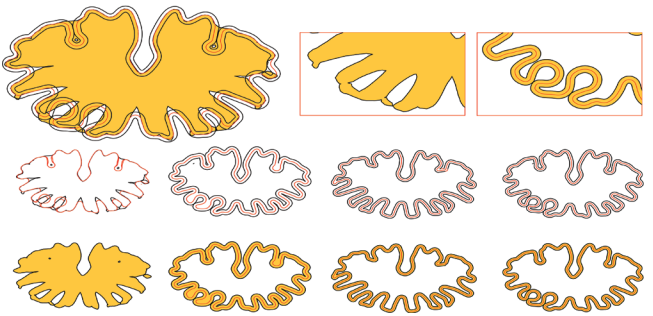
Elimination of Cavities

One of the most important features of the initial design was the complexity succeeded by the voids and cavities distributed unequally and asymmetrically around the mass. According to Pegna, cavities cannot be molded, so AM or else layering construction, is the only way (Pegna 1997). However, though being one of the most challenging parts of the printing process, cavities were eliminated as unprintable elements during the first stage of main build testing because the Eindhoven printing setup—unlike other desktop 3D printing processes—lacks a stopping mechanism and extrudes concrete continuously (Figures 8, 10). The cavities were represented as separate smaller closed curves in the initial contours that were manually removed.

Restoration of Cavities

Although the elimination of this complexity and deviation—i.e. cavities—was necessary at the beginning of the 3DCP process, at a later stage it was reinserted in the form via certain techniques. The first technique was the subdivision via Rhino of the main mass into more sub-volumes in the upper layers—where the CA structure dissolved and scattered—so that the "broken" parts could be built as separate pieces with the continuous extrusion system (Figure 8). In the second technique, the distances between the "spikes" (i.e., extreme curvatures) of generated toolpaths were adjusted in Grasshopper to touch and detach while moving from one layer to another (Figure 8), so that the cavities were distributed in different heights and locations without the need of a stopping mechanism. When they touched, then the outer line seemed continuous, and the resulting volume created at the specific height seemed unbroken (Figure 10). When they detached, the volume appeared broken.

Scale Experiments /
Behavior of Machine in Relation to Different Scales

The scale of the printed objects was directly related to the printing constraints due to the robot kinematics. "If the

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9   3DCP Set-up at TU/e

10 Diagrams of tooling paths for the re-insertion of cavities

curvature of the toolpath is too steep the rotational axis of the robot cannot keep up with the translational axes" (Ahmed et al. 2016). As a result, it was observed that scale was directly related to the machine speed. When scale was small, the end-effector could not maintain constant required speed as very close folds resulted in movements that were slowing its performance. This resulted in a lower printing speed at the sharp corners and consequently in excess deposition of material at those points. Therefore, we increased the scale to attain the desired resolution.

Density of Curvature Reinforcing Structural Capacity
Due to the material performance and characteristics, i.e. curing time, weight, accelerators used etc., the cantilever curvature responded to the properties of concrete and had to be tested and readjusted to produce a self-supporting

structure. The process consisted of many failures as a part of the investigation (Figure 12). Based on the failing tests, we concluded that the density of curvature folding increased the structural performance of the printed surfaces, as the distances to bridge were reduced and there were more connection points between parts of the surface. One test included a Grasshopper calculation of extra linear connections between the spikes and the central mass, an internal ring based on the initial rotational grid on which the CA were proliferated. Instead of a filling pattern, we created a structural pattern with linear connections between parts of the external surface (Figure 11b).

Automation of Readjustments within Grasshopper
To automate the translation of forms—initially classified as unprintable for such set-ups—to printable geometries that follow constraint resolutions, all adjustments of curvature, including cantilever distances between stacking layers, calculation of internal ring, and initial control points of tool-paths, were scripted via Grasshopper definitions (Figure 11). The automation and scripting yielded a toolbox to be used in printing all other unprintable structures generated via the specific CA methodology—regardless of their differentiation and variation—and led to customization and a process prototype focused on optimization of the material deposition at curvature contours that provide structural efficiency through complex geometries.

RESULTS AND DISCUSSION
The printing experiments that took place led to certain outcomes following the main objectives. The research concluded that it is essential to make a further link between unprintable surfaces (that by their very nature present challenges to building feasibility) and fabrication processes of complex geometries. Although the study of the initial design through fabrication constraints is important, of equal importance is the exploration of a link that informs and refers to the post-design stage. Experiments proved that the unprintable parts of a surface—due to their inherent complexity—can lead to robustness. Thus, failure and inefficiency of a component due to its sculptural and aesthetic identity can be connected and eventually lead to structural strength.

As already mentioned, there is a substantial difference between the printed outcomes and the original meshes. Due to the lack of stopping mechanism, the size of the nozzle at the large setup of TU/e, the material properties and the cantilever constraints, complexity and detail had to be eliminated and gradually repositioned. It would have been possible to get closer to the initial mesh by using a nozzle of a smaller diameter and a non-stopping

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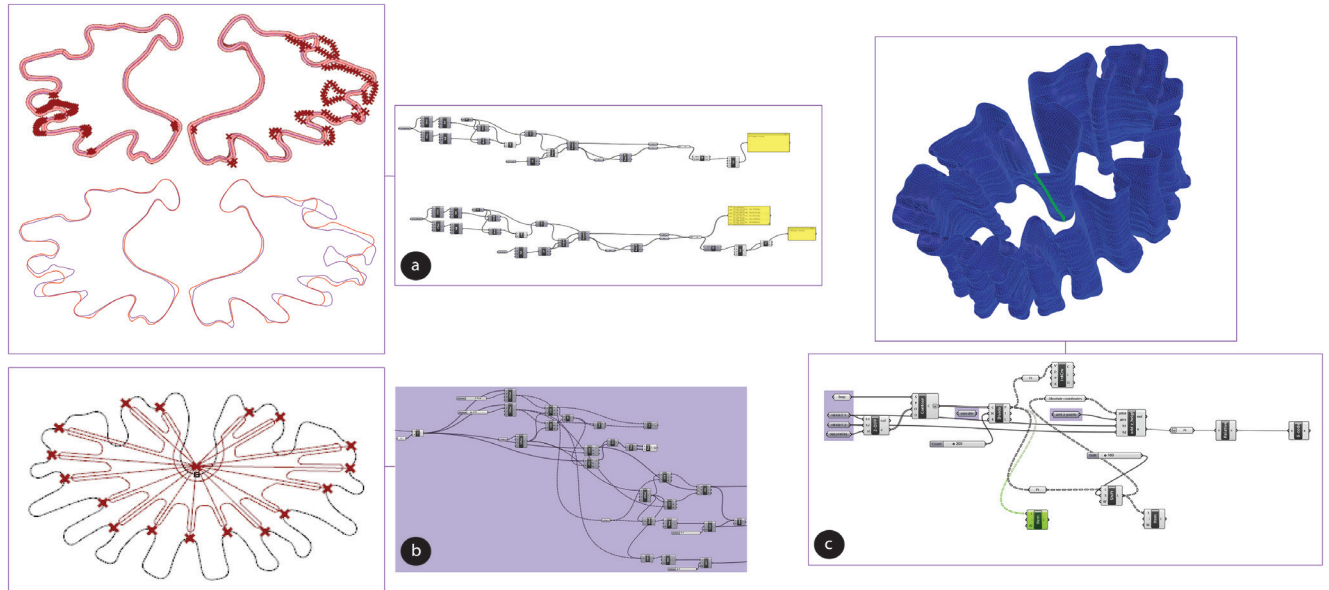
11 Grasshopper tools - Surface and tooling paths for 3D printing: (a) Cantilevers adjustment;
(b) Creation of internal rotational grid for extra support; (c) Alignment of toolpaths origin points on surface

mechanism, which in fact was not available at our location and set-up. In addition, the use of a 5-axis robot would have made a higher resolution possible.

The results or this work are self-supporting structures that can perform as well as structural elements when serving as formwork for a concrete fill in a second phase. Other next steps would include a design generated and customized following the limitations of the specific robotic system, incorporating parameters such as cantilevers, subdivision, extra connections, curvature, and smoothness into the initial algorithm.

In pursuing the fabrication-research question, we engaged with whether it is possible to prototype and mass-produce a customized design. The answer is that this is possible by prototyping the process as a very precise tooling system within which variation is allowed by differentiated parameters inputs and by incorporating different variables. Therefore, besides the printed structures resulting from the above experiments, another important outcome of the work was a process prototype.

Comparing to the main 3DCP techniques introduced in the beginning of the paper, the advantage of this process was the combination of a large-scale extrusion-based method without support, using and converting the complexity (cavities and folds) of the original surface into strong printable elements and load distribution components by creating "proximity locks" between the adjacent points on surfaces. A tooling system translated any unfeasible design

to a robust built element, and sculptural effects worked towards stability. Errors/deviations in form, folds, angles, etc. topological deviations can provide structural properties. Failures can potentially provide new techniques that can generate more robust structures. Aesthetics can be a structural advantage and consequently an optimization benefit. The main contribution of our work to the field is converting from the sculptural to the structural in high intricacy, large-scale complex structures.

The experiments involved clearly several failures, too. In the first set of experiments, the viscosity of the concrete mixture led to the inenability to print taller structures without support in one go. In addition, the width of the material deposited along the tooling path was, due to the above reason, 6 cm instead of the 3 cm that was initially calculated. Further experiments with a different mixture will correct these problems. A smaller radius of the nozzle can also provide more detail.

The translation of the original design mesh to the surface to be printed was performed computationally through Grasshopper scripts that used the original contours as inputs, identified the problematic areas, calculated the necessary filet radius/curvature for smooth nozzle movement, and calibrated the cantilever distances between layers. One could integrate these constraints into the initial computational design. There are, however, two reasons for establishing an alternative process of a later stage correction. Firstly, we sought to incorporate and serve more complex, seemingly unprintable projects and forms,

12 3D Concrete printing process and printing failure

generated using software, that focus on form dynamics instead of fabrication and optimization. Secondarily, a form, or "a family of forms" might be designed through the same concept but serve different scales that will eventually lead to different materials and fabrication technologies with diverse nozzle sizes and cantilever constraints. Therefore, a form needs to be flexible and adaptable to various construction setups, incorporating different manufacture constraints at a later stage.

CONCLUSION

The paper presents the translation of complex design elements with low building feasibility into fabricated objects through the 3DCP methodology and via several material management methods as prototypical fabrication tools.

Although the initial design was based on the idea of error and its role in complexity distribution, in this 3DCP experiment the investigations were focused on the elimination of intricacy as unprintable elements that can potentially be reintroduced to strengthen the printed structure. In further tests, the error concept can coincide with the fabrication technique adjusting the communication between the design code and the material behavior.

Future development and later steps can also include inclined and non-planar cutting planes that perform better as tooling paths in complex cantilever topologies and vaults, distributing the weight sideways (Khoshnevis et al. 2006), as well as recreating more of the original cavities through

the above techniques and through smaller extrusion width nozzles.

Design should adapt to fabrication rules and can produce new fabrication techniques through failure management, the elimination of error/detail, and its re-insertion. However, freedom and complexity can coincide with feasibility, low cost, and material performance. Fabrication constraints need to be embedded into the initial design, yet they should not always lead the design process or create an exclusive manufacturing industry.

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