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A Discrete Roof-Column System With Hollow-Core 3D Printing And Bespoke Space Frames

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PRŌTÓPLASTO
A DISCRETE ROOF-COLUMN SYSTEM WITH HOLLOW-CORE 3D PRINTING AND BESPOKE SPACE FRAMES

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Prōtóplasto, an ultra-lightweight plastic media installation, introduces the novel process of hollow-core 3D printing (HC3DP) to upscale polymer 3D printing (3DP) for architecture, and the novel method of support-free assembly of bespoke space frames (SF) through the geometric articulation of 3DP joints.

The pavilion is a light installation in an upcoming innovation hub in Switzerland and consists entirely of hollow plastic elements produced through 3DP and off-the-shelf parts (Fig. 1). Learning from nature, creating hollow structures paired with smart geometric articulation, one can achieve architectural height and volume with minimum material and weight. The design and fabrication of the pavilion was formulated as a studio brief for the MAS in Architecture and Digital Fabrication (MAS DFAB) at ETH Zurich.

Contextualising the research on 3DP plastics in architecture to discrete, deconstructable, and reconfigurable systems with different properties provides new ground for exploration in 3DP architecture, which until recently was envisioned as predominantly monomaterial and monolithic. The mixed use of processes and systems in this project finds unity in its expression through plastic materials and allows for the exploration of a more playful architecture towards an ephemeral definition of space freed from the constraints of massive, permanent materials used in construction.

Plastic architecture in the digital age

The introduction of plastics in architecture dates to the beginning of the 20th century, when the fascination of architects with this synthetic material sparked the imagination of 'featherweight' houses, in the words of Fuller (2008, p.9). The lightweight quality of the material and high strength-to-weight ratio provided b-products like fibreglass embodied the utopian image of cheap, transportable, bespoke, and organic buildings that could be accessible to all. The acceptance of synthetic materials as the future of architecture in the 1960s provided further ground for modular buildings that would replace concrete and steel. While the fascination with the material soon transferred to light membranes and tensile structures still used today, the production of entire building components out of plastics was put to rest until recent years, when 3DP and especially material extrusion (ME) provided a cost-effective method accessible to all for creating customisable plastic parts of large dimensions using

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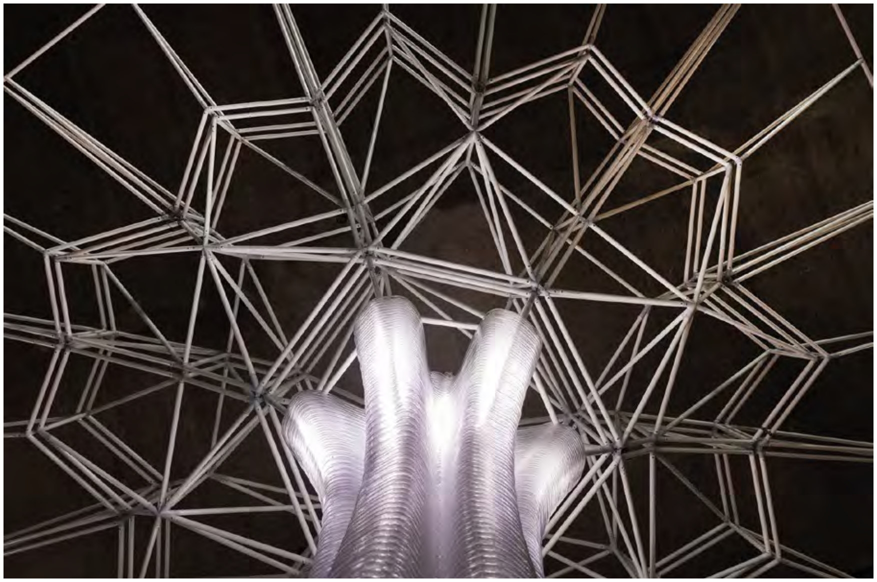
thermoplastic feedstock without moulds or falsework (Vicente *et al.*, 2023).

Contemporary technological advancements have not only eased and democratised the use of plastics through 3DP but present new opportunities to imagine the 'new' plastic architecture in the digital era. Furthermore, the use of synthetic plastics presents an additional material resource that relies on the chemical by-products of fossil fuel refinement processes (Center for International Environmental Law, 2017), thus maximising the use and value of the resources that are already extracted. Their recyclability can be achieved with less consumed energy than other construction materials like metals or concrete, because of their low melting point, especially when not formed into composites. Their reuse is achievable through the durability of many synthetic polymers. In the future, the growing use of bioplastics can be seen as an alternative to synthetic ones as the extraction of fossil fuels is slowly eliminated.



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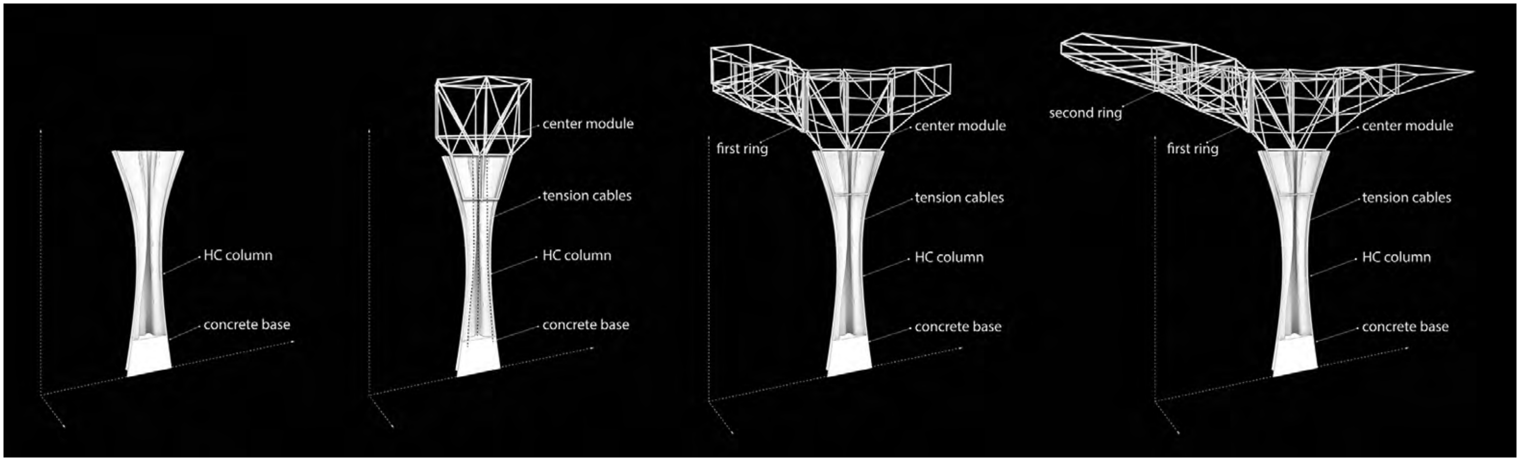
With this project, the authors examine anew principles of lightness, modularity, and temporality in architecture with the mixed use of manufacturing methods and plastics. The goal is to explore new architectural aesthetics, novel production methods promoting material savings, methods for (dis)assembly, and geometric articulation for modular components, as well as pushing the limits of light construction to Fuller's notion of 'featherweight'.

Towards discrete prefabricated architecture

Digital prefabrication of discrete elements is a core principle of *Prōtóplasto* that the authors believe is relevant for the adoption of digital fabrication techniques in construction. In this spirit, the most appropriate techniques, materials, and methods are identified and employed for the different parts of the constructive system. Macroscopically, the structure is a slab–column pair for which two systems are combined to deliver the different properties required for those two elements in the most efficient manner: large-scale ME and 3DP-enabled SFs. Although technical advancements in 3DP have achieved a significant increase in build volume, contemporary approaches result in heavy, material-intense elements. The expanding size of 3DP machines has alluded to the continuous in-situ fabrication of entire buildings. Nevertheless, the fabrication of vertical and horizontal elements in a continuous process at an



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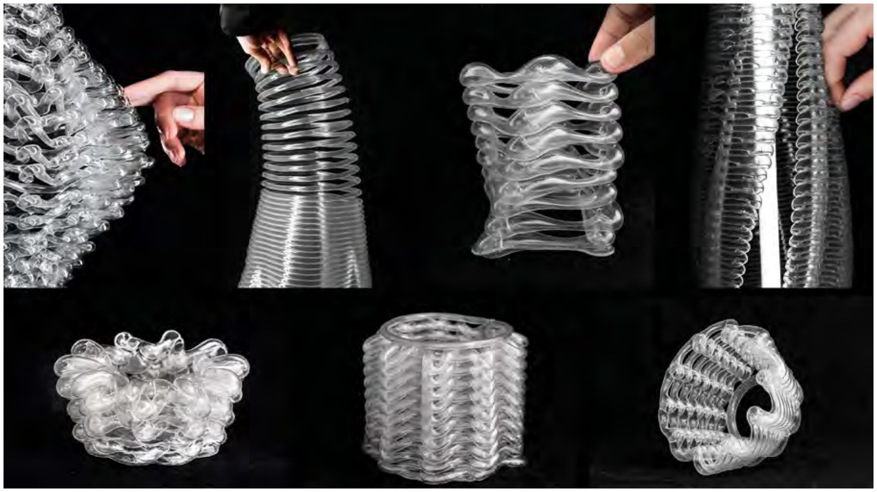

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1. Prōtóplasto exhibition. © Andrei Jipa, DBT.

2. Transition between column and roof structure. © Andrei Jipa, DBT.

3. Assembly scheme. © Matthias Leschok, DBT.

4. Prototype of concrete feet, SCC cast into HC3DP formwork. © Matthias Leschok, DBT.

5. A series of design explorations conducted by the MAS DFAB students 2023. Filament-based HC extrusion with a diameter of 10mm. © Fen Chan, DBT.

architectural scale offers a provocation to actual practice. Therefore, a radical position is presented where the necessity for discrete fabrication is celebrated through differentiated articulation of building elements according to their role and position in the constructive system (Fig. 2).

Large-scale ME offers the opportunity for geometric freedom and high articulation. However, it is better employed for the production of vertical elements, due to the anisotropic behaviour of the layer-based material deposition. The process of ME is scaled up with larger toolheads and extruding thicker and heavier beads (Duty *et al.*, 2017). Investigating methods to upscale ME with lower material intensity and higher volume output is necessary. Elements of architectural size need to be fabricated within hours, not days or weeks. HC3DP at large dimensions, introduced by Leschok *et al.* (2023), overcomes those problems by fundamentally changing the way large elements are 3D printed. With the introduction of HC3DP, the extrusion rate of thin-walled hollow-tubular polymer beads can compete with those of concrete 3D printing, while only using a fraction of the material.

On the other hand, for horizontal elements such as slabs and roofs, SFs present a more efficient system due to their three-dimensional action. Previous research has shown the benefits of 3DP joints for non-standard SFs, including minimising production waste and employing lower-energy-consuming materials (Kladeftira *et al.*, 2022). However, the fabrication of non-standard structures in-situ requires the assembly of individual elements at great heights and heavy machinery. Often, support structures are as dense as the structure itself. In this project the elimination of support structures was studied in combination with a customised modularisation strategy enabled by 3DP joints, allowing for efficient, safe, and fast assembly by humans without heavy or special equipment. Extensive research on connection principles and detailing between modules was performed as well as patterning and sequencing strategies that allow for gradual loading of the structure throughout the assembly process.

Constructive system and digital workflow

The pavilion is conceived as a modular aggregation of three long-spanning mushroom columns. It is composed of a 3D-printed column and a radial SF (Fig. 3). The columns are manufactured with HC3DP with a single outline, while the core of the column is hollow to accommodate post-tensioning cables and light sources that produce the final illuminating effect. The SF roof features a unique topology enabled by novel typologies

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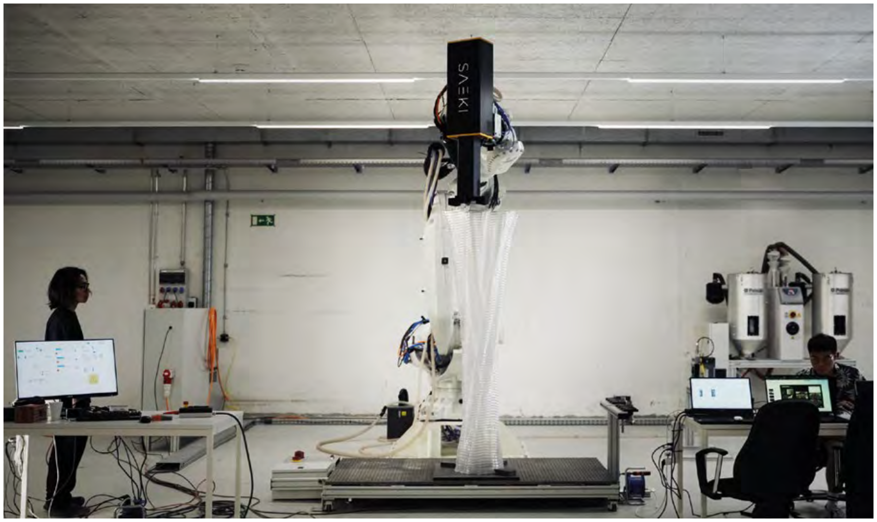

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of 3DP interlocking connections. The roof interlocks with the hollow columns with an intermediate component. The geometry of this SF module is adapted for each bespoke column such that it interlocks with the column's undulating geometry in the upper 25 layers. A post-tensioning cable runs through the central joint of the intermediate module, traverses the column, and is anchored to the concrete footings on which the columns are placed. The footings are shaped in continuity with the column geometry and HC3DP formwork is used to match the scale and resolution of the layered-base materiality of the column shaft (Fig. 4).

Each column–roof pair is designed and fabricated through a computational parametric workflow. Each 'mushroom' reacts to its relative position in the structure and the desired pavilion outline. The parameters for column design include fabrication constraints, such as continuous toolpaths, maximum overhangs, and minimum feature size. The designed undulations augment the stiffness of the 3DP elements in addition to the insertion interface for the SF. The design tool for the joints calculates the minimum joint volume needed to connect the tubes and orients the necessary connection details in order to create unique hybrid-detail connections tailored to their specific position in the structure.

Fabrication setup

To fabricate the pavilion, multiple complementary digital fabrication techniques are used. The columns and concrete formwork are HC3DP using a pellet extruder mounted on a 6-axis ABB 6700. The nodes are 3DP in PA12, with a 48MPa characteristic tensile strength, using the MultiJetFusion technology, a powder-bed process ensuring isotropic behaviour and high accuracy. The linear members employed for the SF are industrial 20mm glassfibre polymer rods. The bespoke-length tubes are cut in a human–robot collaborative setup, in which the human loads the feedstock and the robot slides the tube into the corresponding position for the cut to be executed with a stationary bandsaw. Pneumatic grippers are employed to temporarily lock the tubes' position during this process.

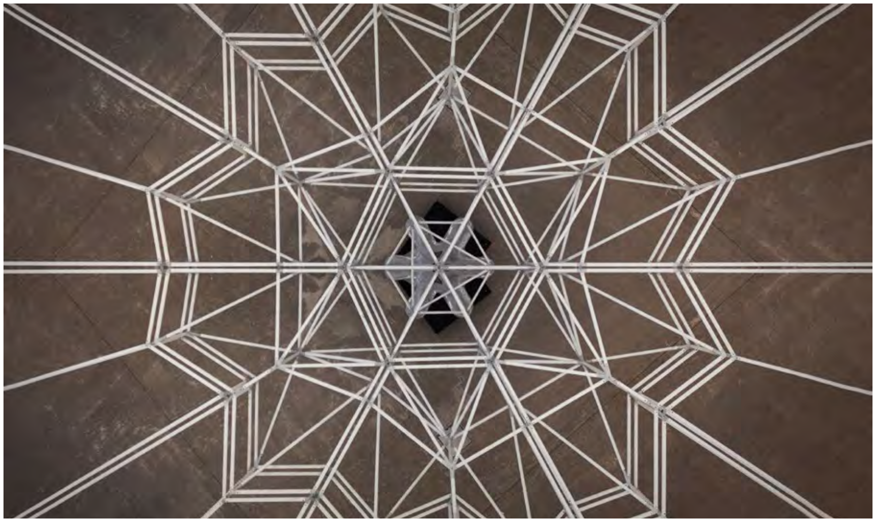
Creating lightweight architecture

In HC3DP, polymer feedstock is used to 3DP large-scale hollow-tubular beads (strands) instead of full cross-sections. This novel approach has many advantages compared to off-the-shelf large-scale 3DP methods, such as high printing speed, through improved cooling rate, reduced material consumption, and enhanced transparency. HC3DP pushes polymer 3D printing into an architecturally relevant scale, as the printing layer ranges from 10 to 24mm, while the build-up rate is comparable to concrete 3D printing (Anton, 2020). High-performance parts can be printed with a wall thickness of 1.0-2.0mm because of the higher strength-to-weight ratio tubular sections display, saving more than 85% of material compared with conventional AM.

PETG was used for the HC3DP of the columns, a co-polyester derived from the commoditised PET polymer, modified to improve its printability and featuring high transparency. Design explorations with robotic filament-based HC3DP were performed to investigate material and process limitations. An off-the-shelf extrusion system was adapted to use the HC3DP technology with a resolution of

6. Close-up of HC3DP process. Diameter of extrusion 24mm. © Girts Apskalns.

7. All columns were 3D printed at the fabrication hall of SAEKI Robotics, using one ABB IRB 6700 industrial robot. © Girts Apskalns.



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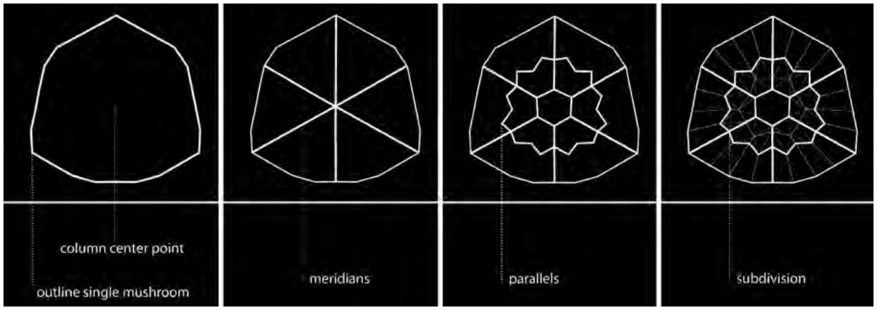

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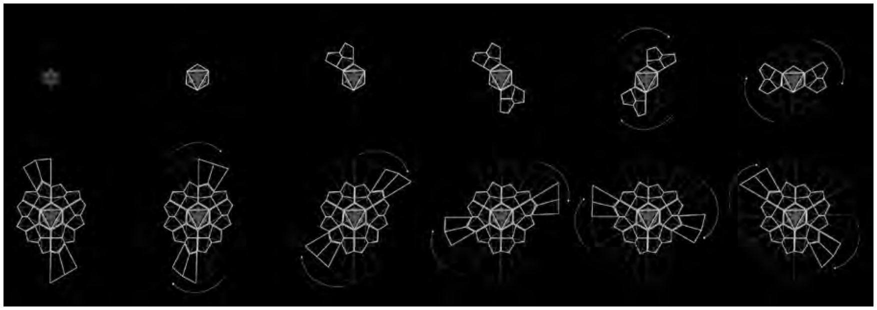

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8. Top view of one mushroom column. © Marirena Kladeftira, DBT.

9. Computational design framework. © Matthias Leschok, DBT.

10. Assembly sequence. © Nik Eftekhar, DBT.

10mm. The new aesthetics enabled through low-resolution, highly transparent polymer 3DP were explored in small-scale prototypes. This new printing technology allows for the creation of elements with extreme overhangs, woven structures, and non-planar 3DP. Elements of medium size were printed to understand manufacturing constraints and design possibilities, as shown in Fig. 5

Over the last two years a robotic end-effector was developed specifically for HC3DP enabling the 3DP of large-scale tubular beads, thereby improving the extrusion rate dramatically. The process was then adapted for the commercial pellet-extrusion system of SAEKI Robotics (Fig. 5). The tubular geometry of the beads is materialised with a bespoke nozzle and positive air pressure. The nozzle splits the molten pellet feedstock into a thin-walled bead and an empty core. Compressed air is injected into the hollow bead to create positive air pressure and prevents the bead from collapsing. For the final design of the columns, a nozzle design with internal bracing was used. The core is reinforced with a ‘X’ cross instead of an ‘O’ section. This was necessary to increase the stiffness of the elements and achieve higher loading capacity.

A diameter of 24mm and a layer height of 19mm was used in the project (Fig. 6). The extrusion rate is 7250mm^3/s (1308 material, 5942 air), rendering the 3DP of the 2.2m-tall columns in only four to six hours and with a weight of 10kg each for the ‘O’ section and 18-20kg for the ‘X’ section. A column with a comparable volume, printed with regular ME (6mm width, 3mm layer height, two outlines, one of them zigzagging), results in a ten-fold longer print time and four to five times higher material consumption.

3DP enabled support-free assembly of modular SFs

The design of the roof is governed by three principles: modularity, support-free assembly, and disassembly through dry self-interlocking connections. The unique constellation of the structure and its non-standard layout require a custom SF enabled by 3DP joints light enough to be supported by the columns and stiff enough to span the 5.5m distance between them, as well as the 3m horizontal overhang (Fig. 8).

The roof is first discretised into three segments, designating the portion of the roof that is supported by each column. Subsequently, each segment is discretised further into modules according to the following principles: a radial array of primary beams (‘meridians’) is formed, stemming from each column outwards to the exterior ring of the SF. Perpendicular to the radial lines, parallel concentric polygons are formed through a subdivision schema ('parallels'). This two-way hierarchical grid and its density defines the amount and number of modules and signifies the axes along which doubling of members will occur. Each module is further subdivided in three-dimensional space, adding diagonals for rigidity and stability during assembly (Fig. 9).

Three typologies of joints were developed. Their geometry is a hollow shell with a seamless connection to the tubes and a 3mm wall thickness which, after mechanical testing, was fine-tuned to match the ultimate tensile strength of the plastic tubes. Two types of intra-module joints feature: a) a socket pin connection for the members of the boundary frame that are assembled first, and b) an intermediate piece for stiffening diagonals first attached via a socket connection to the tube and later fastened on the joint with a self-guiding slit and an interlocking pin. Finally, the module–module connections are formed via added self-interlocking details on the shells of the joints positioned at the interfaces of adjacent modules. They consist of a male–female self-guiding interlocking fork that allows for vertical insertion of the introduced module (Fig. 11).

The assembly follows a semi-circular sequence dictating the position of male/female details (Figs. 10, 12). First the intermediate module is inserted for connection to the column, and subsequently two cross-facing modules of the first parallel are placed to balance the weight. The size and weight of the modules are tailored such that they can be handled by one human, featuring an average weight of 3.7kg. Two people start adding modules radially until the full circle is assembled. Due to the segmentation scheme, all column–roof pairs can be fabricated in parallel with no expertise by crowdsourcing the assembly.

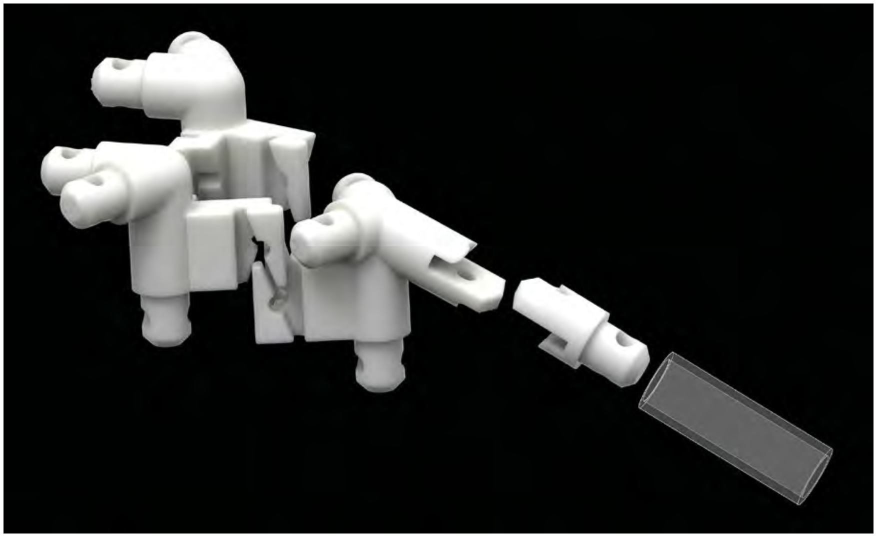
Exhibition

The pavilion is exhibited in an industrial underground setting at Halter AG in Switzerland. The pavilion is exhibited surrounded by suspended HC3DP chandeliers (Figs. 13, 14, 15). No other light sources except for the ones installed inside the HC3DP elements are present in the room, contributing to the installation's dramatic impact.

A plastic future?

Prōtóplasto opens up a dialogue about the controversial use of plastics in architecture along with design-for-disassembly methodologies. It revisits the ideals for lightweight plastic architecture and proposes a new perspective on how to use circularly synthetic materials that can be reused or recycled multiple times during their life cycle. The combination of techniques and materials is an experimental search for more efficient use of materials and systems that leverage digital fabrication technologies and innovate equally in the microscale (material system) and the macroscale (construction system), as is evident from the extremely light weight of the structure at 3.8kg/m^2.

HC3DP provides further ground for experimentation at the architectural scale in building envelopes, formwork creation, ephemeral architectures, and product design such as bespoke lighting. Furthermore, the validation of modular support-free assembly with tailored connection details can provide a basis for future research founded on the same principles as aerial automated assembly by flying machines and collaborative human–drone construction, thanks to the ultra-light character of the modules and self-interlocking details.



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11. Module–module connection to support-free assembly. © Marirena Kladeftira, DBT.

12. Support-free assembly, last element being placed. © Girts Apskalns.

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13. Installation view showing the 2.2m-tall HC3DP chandeliers surrounding the pavilion display. © Girts Apskalns.

14. One of the 2.2m-tall HC3DP chandeliers suspended from the ceiling to frame the exhibition. © Girts Apskalns.

15. A series of 2.2m-tall HC3DP elements aligned and alight. © Nijat Mahamaliyev.

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