THE DUALITY OF CLAY AND CONCRETE

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This paper discusses the duality between clay and concrete within the framework of additive manufacturing. Particularly in the case of 3D concrete printing, the monolithic approach of continuous printing of large-format architectural elements is being prioritised. Contrary to this path, this paper examines modularity and configurability for both 3D clay and concrete printing. This represents a means of extending the life-cycle of components and architectures by designing for reuse and adaptability. This is showcased through a fundamental architectural element, the column. The tectonic expressivness of the developed structures is being discussed through the lense of computational ornamentality and digital craftmanship.

INTRODUCTION

The complex implications of climate change, the climate crisis, material scarcity and extractive industries for our societies are widely discussed and known. The role the construction industry plays in this environmental equation, particularly the use of steel and concrete, are extensively cited at the beginning of numerous scientific papers. The 2024 report by the UN titled "Building Materials and the Climate: Constructing a New Future" states the following: "The built environment sector is by far the largest emitter of greenhouse gases, responsible for at least 37 per cent of the global emissions"[1]. It highlights the importance of decarbonizing the construction sector, particularly through the reduction of embodied carbon emissions. Currently the use of concrete for structural and infrastructural purposes cannot be fully avoided. Additionally, the construction sector is notorious for its slowness in implementing large-scale industrial changes and novelties. Therefore, it is quite likely that concrete will remain in the foreseeable future a commonly employed material. Yet, by complying with the paradigms of circularity by extending the life cycle and reuse of components, its environmental impact can be diminished. This can be addressed by further advancing modularity and reconfigurability in the design process. As discussed in more detail in this chapter, 3D concrete printing (3DCP) is often used following an approach of monolithic production, which hinders reconfigurability and repurposing of the elements themselves. A changed paradigm of modularity for 3DCP can alter this.

While concrete is employed for large-format architectural components relating to structure, clay is a building material that is rather used for the production of smaller scale elements. Historically, clay is a material that has been broadly employed in architecture under the form of bricks and as tiling be it for facades, interiors or as a cladding system for roofs. In building interiors, clay or ceramic materials (the fired version of clay) is encountered in wet zones such as bathrooms or kitchens, as tiling for walls, ceiling or floors. Within contemporary research in architecture, additive manufacturing with clay still covers similar application areas. The PolyBrick 2.0 [2], the Ceramic Information Pavilion composed of 882 custom bricks [3]manufacturing and assembly. In the modern era, this has been perceived as a significant drawback, and as such has resulted in brick construction being partially superseded by more rapid methods of fabrication, despite its inherent robustness and longevity. This paper describes the second stage of an ongoing research project which attempts to revitalize the material system of the brick special through the development of an intelligent 3d printing method that works in conjunction with a layman assembly procedure for a new class of self-supporting nonstandard brick structures. In this project, an indexed and geometrically informed jointing system, together with a parametric and digital workflow, enables rapid assembly on site without a requirement for complex site setup or skilled labor.","container-title":"Intelligent & Informed","event-place":"Wellington, New Zeeland","event-title":"24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA and an interlocking 3D clay printed masonry screen wall developed at the University of Waterloo [4], all showcase computational bricks with varying degrees of ornamental expressivity originating from a computational design strategy. Research projects on ceramic additive manufacturing used for facades are Ceramic Morphologies developed at Harvard University [5] or Clay Non-Wovens developed at Cornell University [6]. Built examples include notably the Seed Stitch wall by Emerging Objects [7] or the finalized 3D clay printed façade for a commercial building in Amsterdam by Studio RAP.

Despite this list of reference projects, clay's potential for architectural applications through the use of additive manufacturing is still underexplored, comparatively to 3D concrete printing. This is the case particularly concerning large format elements such as columns or wall systems. This is of course due to its reduced strength in comparison to concrete and its limited use for structural purposes. Despite these material constraints, the exclusion of clay for such applications may hinder its architectural and tectonic potential. Other than concrete, clay is "a material with interesting environmental advantages: high adaptability to different climates, a low carbon footprint, high resource availability and renewability" [8].

THE DUALITY OF CONCRETE AND CLAY

In architecture, the interchangeability of materials in terms of design is limited and considered problematic. Each material choice implies a particular system thinking in accordance with material behaviour, structural systems and its constructive nature. Material changes require also a rethinking of the fabrication strategy. Replacing one material for another often implies significant changes of the entire system logic, from computational design to fabrication logic.

Liquid deposition modeling (LDM) is an extrusion--based technique using a paste which can be based on different material material mixes. These mixes showcase varying viscosities correlated with adapted extrusion rates and speeds. Therefor LDM allows for a slightly increased flexibility when it comes to the interchangeability of clay for concrete, yet not without its own challenges.

Clay and concrete posess different material properties which come along with their specific set of parameters for robotic fabrication. Due to its structural performance, clay is limited regarding its scalability for large-format architectural elements. Clay has significantly higher shrinkage rates than concrete, and is prone to warping particularly during the firing steps. 3D printed clay may shrink in a non-uniform manner depending on infill types and the geometry of the design. Layer adhesion, buildability during printing and curing times differ too. This translation process and the resulting design iterations as well as changed material expressions will be discussed within the context of selected case studies.

CCP – COMPUTATIONAL CLAY AND CONCRETE PROTO-STRUCTURES

The series Computational Clay & Concrete Protostructures (CCP) was developed in a collaboration between Assistant Professor Cristina Nan and architect Mattia Zucco at the Eindhoven University of Technology. It follows a dual line, being both an ongoing research-lead teaching endeavor as well as a self-standing research line. CCP, as a research-led teaching series, builds up over the past 4 years on consecutive design themes explored in postgraduate seminars and design studios. The aim is to investigate advanced computational workflows and robotics fabrication with clay and concrete not as experimental ventures but as 'normalized' design-to-production tools within the framework of the architectural discipline. Curating process, understood as the loop between design, material and production, stands at the center of this. The CCP-Series focuses on archetypical elements such as the column, the vault, the dome and the skin. Through material experimentation we explore the boundaries of how the ornament and the ornamental may be redefined within the context of computational architecture. Within this writing the outputs relating to the column as an experimentational field will be showcased and explained.

THE COLUMN – A CAROUSEL OF THE MONOLITH AND THE ASSEMBLED

Additive manufacturing has advanced rapidly in the past years in the architecture and construction sector. One of the most common architectural elements through which the potential of 3D concrete printing has been explored is the column. This is not surprising, as the column is integral to most architectural designs and lends itself particularly well for continuous, layered printing due to its verticality. Through the use of 3D concrete printing a wide palette of geometric exploration is opened up for designers, which would be difficult to achieve through traditional fabrication methods. In the project Concrete Choreography [9], layered extrusion printing with concrete is used for the column series. Alternatively, the project Eggshell employs FDM 3D printing with PET-G for the external formwork [10] with subsequent concrete casting. For the Marinaressa CoralTree, a fully recyclable 3D printed sand formwork is used for the casting process [11]. These projects depict monolithic column outputs. Although characterized by a time and labor-efficient production line, difficulties emerge in the next logistical phase. Due to offsite production, the handling, transport and on-site installation of the concrete elements is more complex due to weight and size of the elements. A modular setup allows for an easier fixing or replacement of damaged parts. Reuse and adaptation of the segments remains always a possibility, other than in monolithic fabrication approaches [12].

As the above listed references, the wide majority of 3D concrete printed columns are based on a monolithic approach, meaning that the column is printed as one continuous element. This commonality is rarely questioned and contextualized within architectural history. More specifically, in computational architectural discourse the tectonic evolution of the monolithic is rarely invoked or to begin with understood in its full complexity. A closer study of this topic may offer relevant insights into the positioning of large format additive manufacturing within the disciplinary development of architecture and tectonism.

The history of the monolithic, of the evolution of architectural monoliths (be it fundamental architectural components such as the column or entire architectures) is a complex one and differs depending on specific cultures and across continents. This here built up narrative is by no means exhaustive and is mainly anchored around the extended European ancient architectural history. It serves the purpose of positioning this research within a broader historic timeline.

The term monolith or monolithic is used within this text to describe large-format architectural elements or even architectures (buildings) formed of a single, continuous large block of material. In ancient architecture this material typically would have been stone. The monolithic approach of making or fabrication is atypical in architecture and construction, both in the past and present. Often it presents itself in conjunction with the fabrication logic of excavation or subtraction and not addition as practiced through additive manufacturing. Rock-cut architecture exemplifies best this approach to construction. Vernacular examples of monolithic architecture through subtraction is for instance the Kailash Temple in India. Examples of large-format monolithic architectural elements are the columns of ancient Egyptian temples, the Greek temple of Apollo in Sicily, the portico columns of the Roman Pantheon or the monolithic dome of the mausoleum of Theodoric in Ravenna. Monolithic architectural elements are rare in modern architecture, as it rather follows an approach of integrated tectonic systems. Both in ancient and modern times, the monolithic approach poses significant challenges during its making so excavation, handling and transport. Subsequent changes are hard to implement. Particularly in the case of off-site fabrication, the logistics of positioning are prone to material failure or damage of the element. Due to this, ancient architecture often treats the column as an assembly of parts, be it drums or bricks. Selected examples of vertically stacked drums forming columns are Trajan's Column in Rome, the Delphi Columns, the Acropolis Hill, and the late Archaic Temple of Poseidon at Sounion. Additionally, columns made as assemblies of stacked drums showcase a higher earthquake resistance than monolithic ones. Apart from drums and monoliths, columns were naturally also constructed from bricks and clad with plaster. The Forum Romanum or columns from Pompeii exemplify this technique.

NORMALISING & CONTEXTUALISING AM

One key feature of the CCP-series is the attempt to contextualize computational design and robotic fabrication. Given their nature, research and research-led teaching activities on these topics often focus on the technical and material dimension. Consequently, resulting designs and prototypes are context-free and not site specific. They are treated as standalone objects, demonstrators and exhibition pieces. If additive manufacturing is to be treated as a combined material-fabrication system ready to replace already *today* environmentally problematic systems such as precast concrete or extruded steel, then it needs to be normalized within design studios as a conventional system for design for today's generations of architects. This requires an understanding of the intricate correlations between geometry, material and tool (the robotic arm). Additionally, designing with site-specificity in mind, as within any other architectural design studio, should be a baseline requirement within the academic curriculum for design studios on robotic fabrication. Not doing so, maybe a reason why the technical excellence is not necessarily matched by design originality. Particular images of computationally generated geometries from leading institutes dominate the imagination and awareness of today's designers and students, leading to repetitive, self-referential design proposals with additive manufacturing. It is important to break free from those predefined formal expressions.

Often the physical artefacts resulting from computational research and experimental robotic fabrication in academia are being designed and developed without a specific context or site. This may be valid from a point of view of technological innovation. As a consequence, such prototypes are removed from context, rarely presented as part of a larger architectural framework or composition, being often exhibited as standalone design objects and not architectural elements within a defined context. Digital materiality and complex computational geometries or surface expressions are derived from a self-contained logic, that is motivated through a self-imposed computational challenge rather than contextual considerations. Within the scope of architectural research, we view this approach as problematic. The aim is to inform complex computational geometric approaches and surface expressions via a given context, embedding specific cultural notions in the digital and material workflows.

THE BIO-INTEGRATED COLUMN

The Baths of Caracalla are located in the Southern part of Rome and were one of the biggest ancient bathing complexes. The architectural scheme of the baths is based on a repetition of columns and colonnades, most of which did not survive the centuries. Some of these were monolithic granite columns, others made up of drum segments [13]. Part of the maintenance strategy as the ruins is to keep flora and fauna under control within the historic site. The bio-integrated column was developed to accommodate in a responsible manner plant growth and to offer spaces for inhabitation for birds and insects. A site-specific research resulted in a defined group of plants and animals to inhabit the cladding system (fig. 1). In the development of the column system aspects such tectonic expressiveness through ornamental expression played an important role, beyond the mere functionality of the column itself.

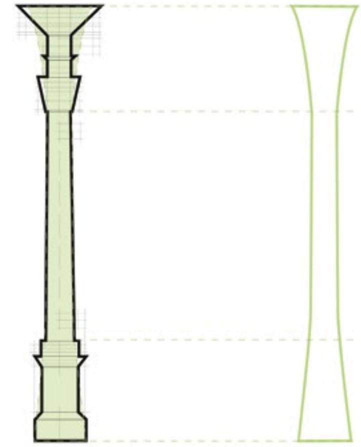
The bio-integrated column originates in the idea of developing a ceramic cladding system mounted onto a structural steel pole in which computationally derived ornamentality of the skin is used not only as an expressive means but as a substrate for nature-inclusivity and biodiversity. Subsequently, the functional and ornamental logic of the 3D clay printed cladding system was adapted and translated to a column system, fabricated through additive manufacturing with concrete. The translation process and the material iterations will be described in the following subchapters.

CERAMIC CLADDING SYSTEM

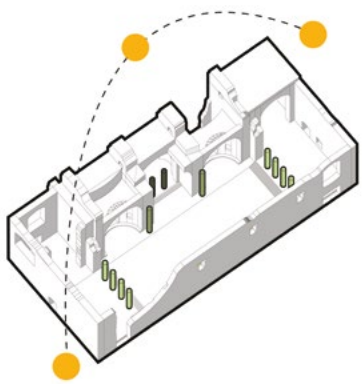
The ceramic cladding system integrates planters for short-rooted vegetation paired with two types of surface articulation for insects, birds and small-scale animals to grasp onto. The size of the pockets on the columns is determined by the spatial needs of native plants observed growing on ruins in Rome [14]. The plants were further grouped and distributed on the site based on their sunlight and spatial requirements, such as root depth and height. For example, plants that grow vertically and require substantial space were placed in the lower pockets, where they had room above them. Those with high sunlight needs were positioned on the southern, sunnier sides of the columns. In order to prevent the accumulation of water within the pockets leading to the rotting of the roots, the ceramic pockets contain drainage holes. These are incorporated directly within the g-code or printing path. The ornamental pattern on the planters resembling pulled strings provides a rough surface area for birds, small reptiles or mammals to hold on to, facilitating a vertical movement along the column. Additionally, this three-dimensional pattern is meant to accommodate moss growth and the inhabitation by insects.

Modularity and reconfigurability were relevant design parameters for the cladding system in order to facilitate adaptability to different sites and replaceability of potentially damaged components. As depicted in figures 2 to 4, different subdivision strategies for the ceramic skin were tested based on 3 and 4 segments mounted around a vertical steel pole to then individual ceramic drums to be vertically stacked along the pole. The step from a 3 or 4-part interlocking system, although successful, to a full drum-element is motivated by the intent to further simplify the assembly sequence. The interlocking cladding system

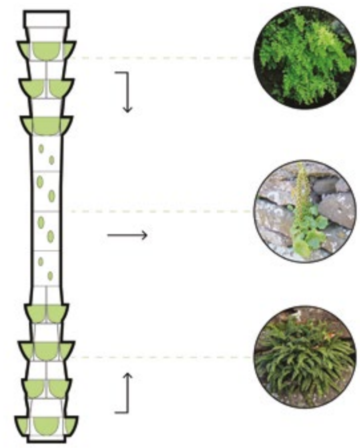
1
CONNECTING TO THE RUINS
Design incorporating greenery as a reflection to the site's genius loci - growth to new life throught the ruins.



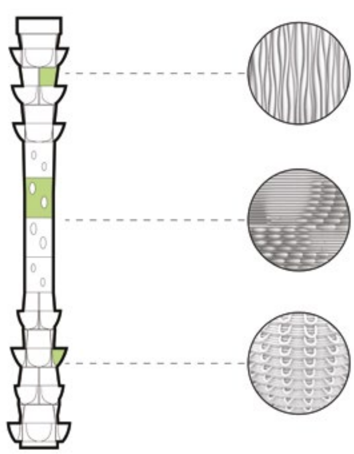
2
PROPORTION STUDY
Column general form derived from taking reference of the ratio and proportions of Corinthian columns that sre mostly found on site.



3
PLANT TYPES DISTRIBUTION
Plants types (climbing, horizontally, growing, hanging) are distributed reflecting on the general hourglass form of column.



4.
SUN HOUR ANALYSIS
Total hour of sun exposure on column positions determine types of plants distribution (sunny / shady / versatile).



5.
POROSITY & TEXTURE
Textures are implemented on the wall and pockets of columns in gradual transition to provide growth surface for plants.

Figure 1: Site integration and relevant design parameters for the 3DCP column within the Baths of Caracalla (Image: TU/e, Nikolett Ásványi, Loy Xin Yi, Maria Verhulst Babb, Maia Kilch)

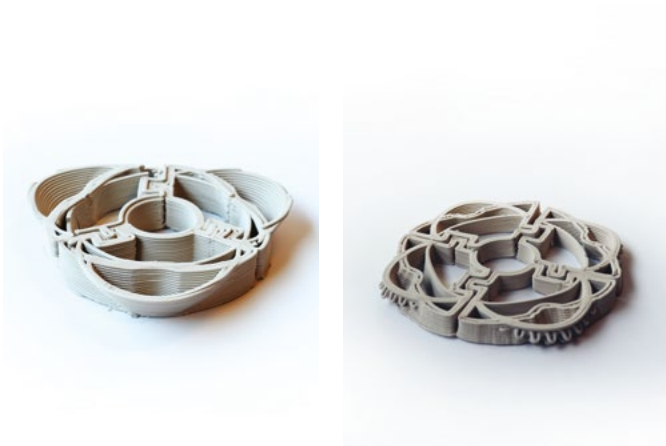


Figure 2: Three and four-part cladding prototypes, 3D clay printed (Photographer: Dena Khaksar).

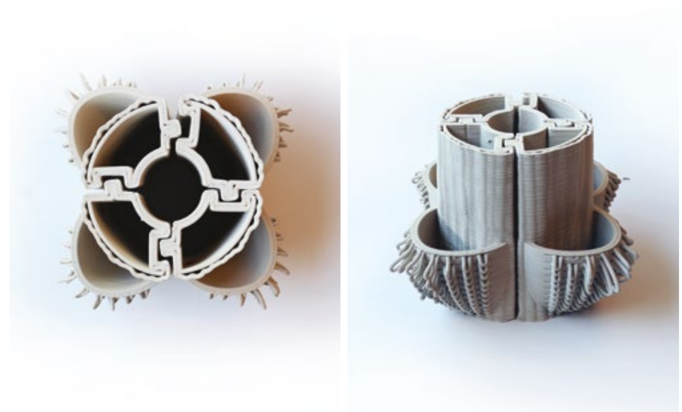


Figure 3: Four-part cladding prototypes, 3D clay printed, (Photographer: Dena Khaksar).

Figure 4: Singular cladding component showcasing ornamental computational patterns, 3D clay printed (Photographer: Dena Khaksar).

Figure 5: circular 3D clay printed drum segment (Photographer: Dena Khaksar).

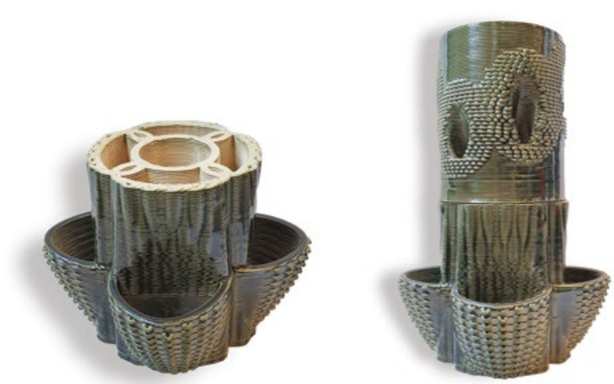


Figure 6: glazed and partially stacked 3D clay printed drum segments (Photographer: Dena Khaksar).

requires an additional fastening system between the cladding and the vertical steel profile. By opting for a stacking system this becomes obsolete.

SET-UP FOR CLAY PRINTING

All material experiments were undertaken with a WASP 40100 LDM with a 4 mm diameter nozzle, a layer height of 2mm and connected to an external continuous feeding system which guarantees a consistent material flow as it replaces the need for a tank with a compressor. For all prototypes a double layer wall thickness was employed to increase the stability of the elements. Commercially available clay with 25% chamotte as a wet paste was used, without additives. To improve viscosity for 3D printing, only an added 2.8% water was mixed into the clay with an industrial mixer for homogenization. The experiments were conducted at room temperature within the digital fabrication laboratory. Printing speed and flow vary during the fabrication process. These variations are related to the component height and specific computational pattern to be printed. Depending on the geometric articulation, 3D clay printing poses challenges related to non-uniform shrinkage and warping, both during the drying and firing stages. Based on prior experiments with ceramic additive manufacturing, closed volumetric geometries such as the drum-like components present little to no warping during drying and firing (fig.5). Segmented geometries or interlocking systems are more prone to warping and non-uniform shrinkage, thus affecting the functionality of interlocking joints. The simultaneous printing of the segments in their assembled position will significantly minimize or fully prevent warping during the subsequent drying process [15]this paper presents a hybrid method for designing with 3D printed clay that combines craft-based and theoretical ways of thinking with simple computational procedures. The method is described through the design and fabrication of an experimental ceramic cladding system for structural steel that allows the architect to consider how to dress a column with clay.","container-title":"Structures & Architecture: A Viable Urban Perspective? : Proceedings of the Fifth International Conference on Structures and Architecture (ICSA 2022, [16]the column. The Computational Clay Column is treated as double system made out of core and skin, both fabricated with 3D clay printing. The underlying principle is the spatial self-interlocking of the two subsystems, core and skin, thus eliminating the need for a substructure or fastening. A particular emphasis is placed on the infill beyond its stabilizing function. Expressive and ornamental value is not only assigned to the skin but also translated to the infill. Based on a conceptual strategy of unwinding, the infill is punctually exposed, showcasing it to the viewer and amplifying the ornamental aesthetic and digital materiality of the computational design strategy and robotic fabrication logic. By exposing the core with its ceramic self-interlocking system, the tectonic expressiveness of the column as an architectural archetype is amplified. The research discusses the computational workflows, material experimentation, the interlocking and assembly logic, fabrication strategy as well as the concepts of digital craft and digital materiality. The applied methodology is based on research-through-design. No prioritization is given to form over material and process of production. The knowledge derived from analog and robotic material experimentation as well as clay's specific material behavior relating to drying, shrinkage and warping are used to inform the design, production sequence and fabrication logic.","DOI":"10.52842/conf.ecaade.2024.1.055","event-place":"Nicosia","event-title":"eCAADe 2024: Data-Driven Intelligence","language":"en","page":"55-64","publisher-place":"Nicosia","source":"DOI.org (Crossref. The same strategy is also applied during the two firing stages: the components are placed in their interlocked position. The first firing is a bisque firing at 800 degrees, followed by a second round at 1200 degrees for the glazing (fig.6). Through the firing the clay body is transformed into the material group referred to as ceramics. Due to this approach, both the segmented cladding system as well as the drum-like segments did not present any warping during the drying or firing process allowing for an unproblematic assembly.

The resulting ceramic cladding system is lightweight, easy to assemble and disassemble. Due to the material behavior of clay it presents structural limitations, posing difficulties in scaling up the system. The depicted prototypes fit within a radius of 25cm and their structural performance depends on the inner steel pole. Scaling up the radius as well as the height of the clay drums brings along further production difficulties. Larger segments necessitate an increased drying time. The clay body needs to be fully dry before firing, otherwise cracking or even small explosions during firing within the kiln can happen due to remaining humidity within the clay. Due to the mass and density of the clay drums in their reduced scale of 25 cm, a drying time within the lab space of up to 4 days is required. In the absence of a drying chamber, this time would significantly increase, leading to a production process that would be inefficient from the perspective of time-efficiency. Further limitations are imposed through the size of commercially available kilns. In order to be able to transgress from a cladding system for columns to an actual column, another material choice was needed. This led to the transition from additive ceramic manufacturing to 3D concrete printing.

TRANSLATION FROM CLAY TO CONCRETE

The logic of the ceramic cladding system had to be altered in the translation process from clay to concrete, a process not without its own challenges. The column height was adapted from 200cm to 310cm, with a constant drum height of 27cm and alternating diameters ranging from 43cm to 39cm (fig. 7). The large format printing requires a rethinking of the slicing strategy as showcased in figure 8. All prototyping is based on the use of internally developed slicers, no commercial slicing software is being used. Due to a change of the layer height and width when working with concrete, the resolution of the ornamental patterns had to be adapted. The layer height was significantly changed, from 2mm for clay printing to 7mm, as well as the layer width from 3.5mm to 21mm. The modification of the printing parameters results in an altered architectural and tectonic expression which could be characterized as 'monumental' compared to the materiality of clay.

This alteration led to a decreased resolution of the base pattern, while at the same time offering an increased stability of the pulled string pattern. The pulled string pattern on the planters is further accentuated by the means of intended over-extrusion. In prior clay experiments, even in its fired form, the pulled string pattern could be damaged with relative ease due to the thin layer width and its relatively large overhang. Top and bottom parts of the columns are equipped with in-built planters, whereas the drums that make up the shaft showcase dispersed deep recesses. These indentations are meant to offer a protected nesting ground for insects and small reptiles.

Although the concrete version of the computational column could have been printed as a monolith, the logic of modularity and reconfigurability was maintained. The resulting column design is based on 11 drum segments and 2 caps, one for the base and for the top. The top cap prevents rain water from accumulating within the interior of the column whereas the bottom one creates a shadow line between floor and column. In order to increase structural stability, pipe-like extrusions, "necks", were added to the top of each of the 3D concrete printed drums. Due to the increased size of the printed concrete layers, the seams that during printing when moving upwards from layer to layer can be visually very dominant. These have to be addressed as an integral part of the design and not just a byproduct of fabrication. For this purpose, the printing seams of the planter segments are rendered invisible through articulation of the geometry by being integrated within the folding edge of the planters.

ASSEMBLY

As mentioned beforehand, the column is made up as a modular interlocking system, designed for dry assembly, meaning without the use of mortar. The complexity of logistics of transportation and on-site handling are thus significantly reduced. The column drums alternate in their individual weight between 25 and 50kg. Up to a height of 150cm the different drums can be stacked manually. The presence of the vertical necks integrated on the column drums increases the stability of the column. After a height of 150cm the drums are stacked with the help of a forklift or a cherry picker (fig.9). Due to the modularity of the drums, these can be assembled in different sequences, allowing for reconfigurability. Relocation within a different context and its adaptation to it by for instance changing its height is made possible.

PIGMENTATION AND COLOR SCHEME

Clay requires a double firing for glazing and color, once at 800 degrees, bisque firing, without glazing, followed by a second firing stage with glazing at 1200 degrees. This double-process is energy intense and significantly increases the carbon footprint of ceramics.

Contrary to popular perception, ancient building sites often exhibited vibrant color combinations in the interiors and on the exterior facades. Leaning on this tradition, also in case of the 3D concrete printed column, a decision was made to integrate color to further articulate the ornamental expression of the skin (fig. 10 and 11). For 3D concrete printing, within the custom robotic setup of our industrial partner Vertico, a 3D concrete printing specialist, pigment is mixed directly with the concrete during the printing process. This allows for custom color gradients and pigmentation strategies. A graded green color scheme was chosen to allow the blending in of the column within the context of the Caracalla Baths. In figure 12 the spontaneous inhabitation by a snail of the on-site mounted column is documented.

CONCLUSIONS

Implementing concepts of modularity and reconfigurability to 3D concrete printing harbors an immense disciplinary potential for the understanding of tectonics through the lens of additive manufacturing. Implementing systematically these two approaches can extend the boundaries of architectural flexibility, scalability and reusability for large-format additive manufacturing. Replacing the monolithic mindset with the modular one in AM allows for on-demand replacement, repurposing of components as well as for scalability over

Figure 7: 3D concrete printed stackable column drums
(Photographer: Cristina Nan).

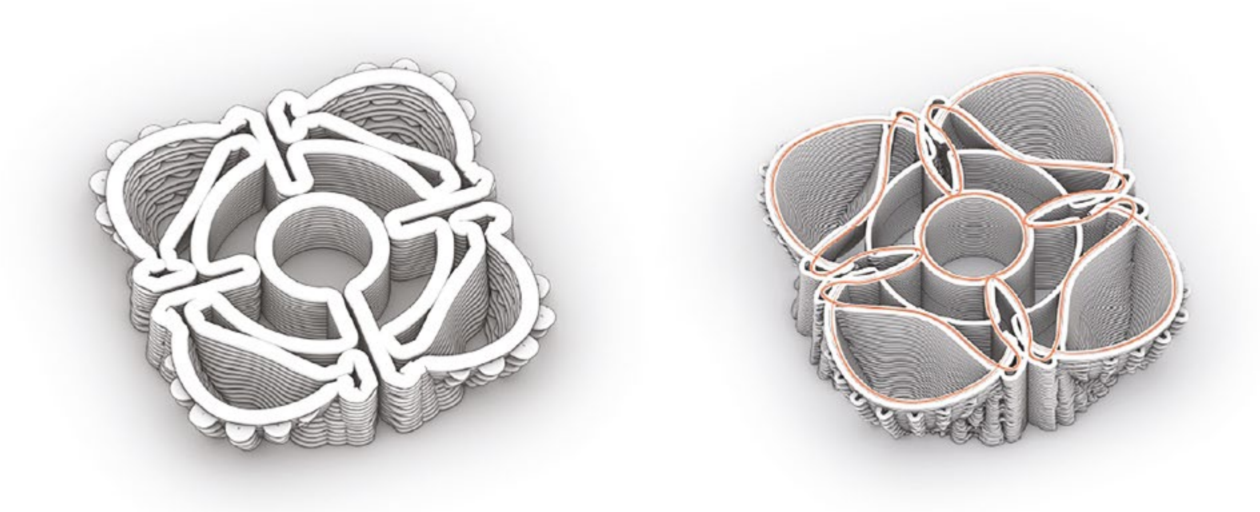


Figure 8: Column drum in concrete vs. clay .

Figure 9: Assembly sequence at Dutch Design Week 2024
(Photographer: Yorit Kluitman).

Figures 10-11: Assembled 3D concrete printed column showcased at Dutch Design Week 2024.

Figure 12: Close-up of snail randomly inhabiting the concrete surface, Dutch Design Week 2024(Photographer: Dena Khaksar).

time by adding new modules to prior fabricated structures to extend their functionality. The shift from monolithic printing which results in "static" structures to modular 3D concrete printed assemblies, can be interpreted as a shift towards adaptable, scalable and thus "dynamic" systems in 3DCP.

FUTURE STEPS

Engaging with the duality of clay and concrete continues as part of the CCP-series by further extending the modularity concept for columns. The column is not only viewed as an assembly of drums, but is being further applied by a subdivision into skin and core components. First experiments based on the interplay of clay and concrete have been already undertaken. This sub-line of investigation runs for now under the title "Unwinding the Column". As shown in figure 13, skin and core of the 3D concrete printed column are visibly detached from one another. This logic of segmentation and conceptual delamination will be followed by separated functional integration within the skin and core such as ventilation, cooling or light installation.

If successfully executed, the balancing act between computational customization and the constraints of modularity can offer higher returns on efficiency, expanded life cycle and material use.

ACKNOWLEDGEMENTS

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- The concept of the bio-integrated column was developed as part of the CCP-studio series by the students: Nikolett Ásványi, Loy Xin Yi, Maria Verhulst Babb, and Maia Kilch. The computational design and optimization for robotic fabrication were addressed by Nikolett Ásványi, Mattia Zucco, and Cristina Nan.
- The "Unwinding the Column"-Prototype was developed as a collaboration between Cristina Nan and Mattia Zucco, relating to the ongoing CCP-series. Additional computational support was offered by Nikolett Ásványi. The column was executed in collaboration with Vertico (NL) and the specialist company Lanxess (DE) which provided the pigments and correlated expertise.

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Figure 13: "Unwinding the Column", 3D concrete printed column showcased at BE-AM 2024, Frankfurt (Photographer: Malcolm Unger).

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