FUNCTIONALIZED BRICKS: ADDING VALUE TO BUILDING CERAMICS THROUGH ADDITIVE MANUFACTURING

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Contrary to several other AM (Additive Manufacturing) technologies, the 3D Printing of ceramics is not suited for architectural on-site production. Mainly limited by the crucial necessity of a subsequent firing process, this technology may only be used in workshop conditions. Nevertheless, ceramics have a high relevance, as well as a rich history among building materials. This chapter presents suitable application cases in the field of tension between a new technology and a traditional material.

INTRODUCTION

Looking at the use of ceramics in building construction, it is noticeable that components made from fired clay do not only prove their versatility through a broad range of applications, but also through their long history of utilization. In the 5th Millenium BC, ancient Babylonians noticed how firing dried clay bricks rendered them into ceramics, making them more resilient to loads and environmental influences [1]. As this knowledge spread, new applications emerged, including rooftiles, pipes, and glazed tiles - each making use of the material's favorable properties in their own way (Figure 1). In particular the fact, that clay is easy to put into almost any shape while moist allows for such a wide variety of utilization.

Along with the industrialization in the 19th century, inventions like the extrusion process and Hoffmann's Kiln [2] led to higher yields and made ceramic bricks a main building material in Europe's cities at the *fin de siècle*. Though in the early and mid 1900's competing materials such as aerated concrete or calcium-silicate appeared, ceramic bricks still hold about 1/3 of market share for residential buildings in Germany [3]. Same is for other applications: even though rooftiles from cast concrete or bathroom objects enamelled metal or PMMA (Polymethyl methacrylate) are available, none of them yet was able to force their ceramic counterparts out of the market.

While geometrically more simple-shaped are traditionally created in an extrusion process, complex objects

Figure 1: The versatile use of ceramic components in a facade. Klinker Bricks alongside glazed tiles and rooftiles, as well as ornaments such as pinnacles. (Hospital de la Santa Creu i Sant Pau, Barcelona, Spain).

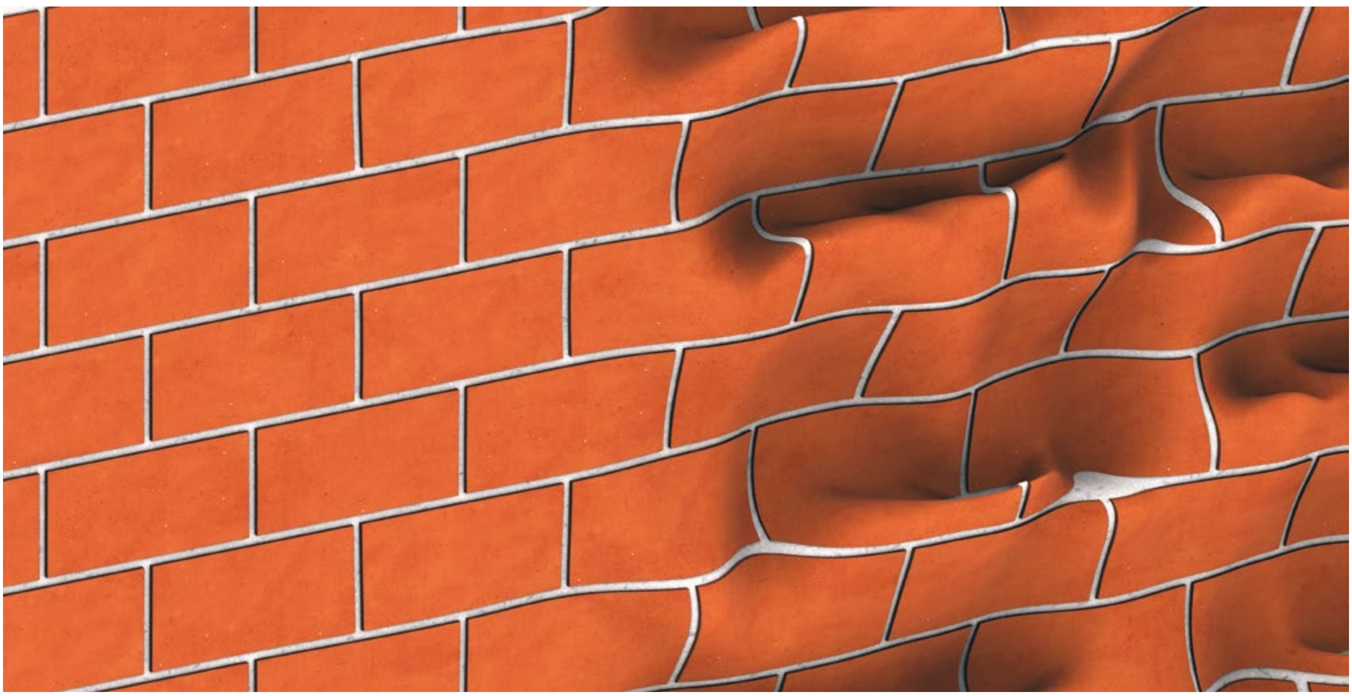

Figure 2: Transition from a planar surface to an undulating one.

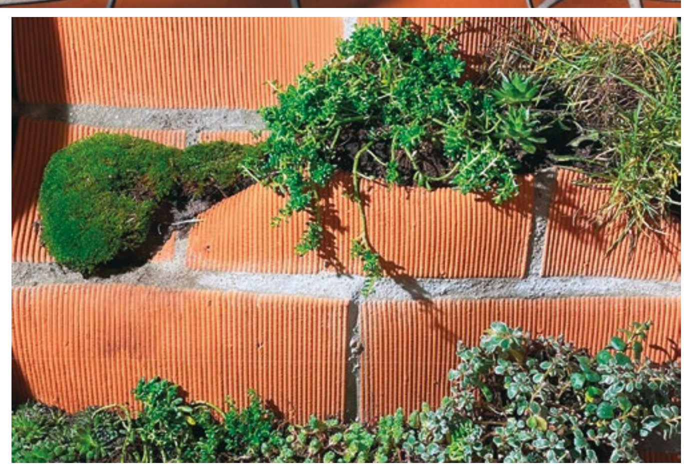

Figure 3: Greened façade hosting undemanding plants. Note the vertical layer artifacts in the bricks.

such as sinks are cast into gypsum formwork using a more viscous clay-slurry [4]. Along with the rise of AM since it's early steps in the 1980s [5], along with a variety of other materials, methods to 3D print ceramics came up. Though there is a broad field of different technologies to do so [6], only Robocasting [7] appears capable of creating objects in the size needed for architectural applications [8]. In this extrusion-based process, a geometry is built up line-by-line and layer by layer. Though this technology comes along with several challenges, as discussed in an earlier Volume of AM Perspectives [4], a multitude of projects has already been carried out [9]. By overcoming some of the aforementioned challenges through research [10,11], now the way appears paved for an industrial implementation [12].

APPLICATION CASES

While AM technologies for other materials, such as steel [13,14] concrete [15] or (unfired) clay [16,17], are well suited for the in-situ production of whole buildings, the AM of ceramic objects lacks this ability. This is mainly due to the crucial necessity of firing the pieces to render dried clay into ceramics at about 1.000-1.200°C, depending on the desired properties of the final material. As this usually takes place in large tunnel kilns, production can only take place at industrial facilities.

Further, being limited to sizes of about 50 x 50 x 50cm, due to limitations while shaping, as well as distortions during drying and/or firing, ceramics crafted through AM may rather be perceived as medium-sized components, than as large-scale modules such as walls.

In addition, their production is very time-consuming. While a stone can be formed in just 3 seconds in the conventional extrusion process, robocasting requires almost 50 minutes to produce a comparable geometry [12], assuming a low printing resolution. Given these preconditions, from an economical point of view, it is advised to use 3D printed ceramic components mainly as a supplementary in combination with conventionally manufactured components [18].

Looking at projects carried out in this field, it is noticeable that many of them merely made use to create ornamental shapes, rather than to add functionalities beyond aesthetics [9]. Furthermore, the use of AM ceramics in a complementary manner was only executed in only one of the reviewed projects [19], in this case, however, again without any specific functionalization.

The following sub-sections present several projects using AM in order to functionalize ceramic building components. All projects were carried out using Robocasting with respect to the aforementioned prerequisites.

GREEN KLINKERS

This research was carried out in an attempt to include façade-greening into double shell masonry made from facing bricks [20]. Using generative algorithms, undulating surfaces were generated, featuring pockets able to hold substrate for greening. The system is able to be integrated into common double-shell brickwork's outer layer by smoothly transitioning from the planar surface into the undulating one (Figure 2). This takes place with respect to the format of the bricks, as well as the bond in which they are arranged.

Since only bricks fired at high temperatures possess the favourable properties for use in facing masonry, the special shaped components were fired at 1.150°C. As their geometry partially provided steep overhangs, it was decided to manufacture them turned 90° to avoid the use of support structures, as well as to create their curvature in better detail. This led to the result, that the layered appearance, characteristic for many 3D printing processes, in this case appears as vertical lines on the surface (Figure 3). As strategies to overcome such had not been researched at the time this project was carried out, the surface of these special components does noticeably differ from conventional brick's surfaces. Nevertheless, it can be stated that most of the post-processing methods for surfaces found later [11] are applicable, making harmonized appearances now feasible.

For greening the façade, the grooves in the undulating surface were filled with substrate first. Then, a variety of undemanding crops, such as *Sedum, Sempervivum, Dianthus Petraeus, Achillea collina, etc.* were planted into these (Figure 3). Most of these plants are common in greened roof systems and known for their undemanding nature. This happened in the expectation to so create a low-maintenance system, which may only receive its water through outside weather conditions.

After production, the 50 x 50 cm demonstrator was monitored for seven weeks to assess the plants accrual and condition. Though from the 15 plants used, most adapted rather well, unfortunately 3 did not survive the experiment. Nonetheless, the study was perceived as generally successful, even though for another iteration certain adaptations may be advised.

Looking at the functionalization aspects this article focuses on, several aspects can be concluded for Green Klinkers. First, from the perspective of geometry, the project included a low-tech kind of functionalization merely through an articulate and complex geometry. Secondly, from the production aspect, no approaches to overcome the aforementioned limitations of the Robocasting process have been undertaken. Finally, a complementary use of specially shaped components can somewhat be recognized, as planar bricks fade over to undulating ones. However, to achieve a greened façade, even if only partly, a greater number of AM Components is required, leading to high efforts in production and the resulting costs.

THE NESTING BRICK

Dealing with an already market-available product, this project focussed the digitalization of a yet manual process to shape specialized bricks. Hagemeister GmbH, a German brick manufacturer, provides several types of hollow ceramic elements serving as nesting-opportunities for endangered species, that flushly blend in common masonry façades (Figure 4). However, their production is still carried out in a fully manual process by one artisan craftsman. This not only leads to high unit-prices and a production capability much lower than the request for the project. It also puts at risk the long-term availability of such products as the skilled craftsmen for such products went almost extinct.

In an approach to digitalize the production of this highly specialized components, first the manufacturer provided digital Models of some of their products. To assess their usability for AM and to identify challenges in their production, these were sliced and printed without much prior reflection. This attempt clearly revealed several challenges of the idea of a "straight digitalization", such as unreasonable long printing paths, which in turn led to long processing times. Also, some geometrical features had to be altered, in order to not fall victim to the printer's low resolution. Further, overhanging and bridging areas required support material, which was also required in several cases to prevent distortion and cracking during drying and firing. Lastly the layer-artifacts in the surface prevented their integration into commonly produced masonry.

To overcome this, several optimizations have been carried out. First of all, a favourable setting for strand-width and layer height was determined. Then, the geometry was rebuilt with respect to the dimensional system given by these two parameters. Also, geometries were re-oriented to minimize overhang and bridging areas, though in some regions additional support structures were still required to enable production. Following the printing, facing surfaces were processed in order to achieve a more harmonized appearance in comparison with commercial bricks. Lastly, after firing at 1.200°C, anti-distortion-supports were cut out and all pieces were assembled into a demonstrator (Figure 4).

On the end of this iterative process, a time-saving of 15% on average was achieved, while in general processability was enhanced. Figure 5 provides a direct comparison of the first and iteration of a Nesting Brick, which is suitable as a habitat for bats. Overall, the study was perceived as successful, as the digitalization of a yet manual process through AM was achieved. Nevertheless, prior to a transfer of this methodology into an industrial context, several adjustments are advised [12].

In view of functionalization, the Nesting Brick again provides a low-tech functionality, but this time through a non-complex geometry. In terms of production, the transfer from an artisan manual process to a digitalized one represented the challenge of the project. This succeeded primarily through a "redesign for additive manufacturing", going hand in hand with applying findings from other research [10,11]. With a view to the economical use of AM ceramics in a complementary way, the Nesting Brick appears much more efficient in adding value through functionalization to a brick wall compared to the aforementioned greened façade, as less components are required to achieve this.

HERITAGE-BRICKS

Throughout this still ongoing research, it is envisioned to use AM Ceramics in order to replace broken or missing pieces in historic buildings. The scope of application for this ranges from creating rather low-detailed profiled bricks, over to reprint complex ornaments such as the glazed pinnacles seen in Figure 1. Due to their rich history, ceramic components occur in a multitude of historic buildings. With their maintenance, not only cultural heritage is preserved for future generations, but also sustainability is granted through their long-term use. Nonetheless, this is perceived only as a technology and how far to go with such replacement-methodologies may be decided by building history experts in each individual case.

Starting with geometrically low-complex parts, profiled bricks have been printed, mimicking existing components as used in cornices, lintels or pilasters (Figure 6). Originally, such 2 1/2-dimensional shapes used to be created in greater numbers using dies or specialized mouthpieces for extrusion. As in replacement-situations the required number of pieces is often too low to justify the creation of such formwork, AM appears as a suitable manufacturing method. Harmonizing surfaces may take place as discussed before in a post-processing step.

However, with regard to more complex geometries, the AM of Ceramics could unfold its full potential. In an attempt to recreate the articulate surface of a cornice composed from glazed ceramics, 3D Scanning was used to capture its geometry (Figure 7). Contrary to the paradigm that printing may take place with the largest nozzle possible, in this case mapping the detailed surface will require a high resolution and result in long processing times. While overhanging and bridging areas will not require support-structures, another challenge is to be seen in the surface-treatment. Though generally proved as feasible in other projects [21–23] little to knowledge is publicly available on glazing AM ceramics. as Being a project still in progress, yet soon to be finished, results on this are expected to be published in the near future.

Evaluating this methodology in terms of functionalization turns out to be more difficult than in the two aforementioned projects. Not only the geometric complexity differs from the individual components to be recreated, but also

Figure 4: Three different Types of additively manufactured Nesting Bricks in a Demonstrator.

Figure 5: Directly printed and optimized Nesting Brick in comparison.

Figure 6: Profiled Bricks for cornices, lintels or pilasters.

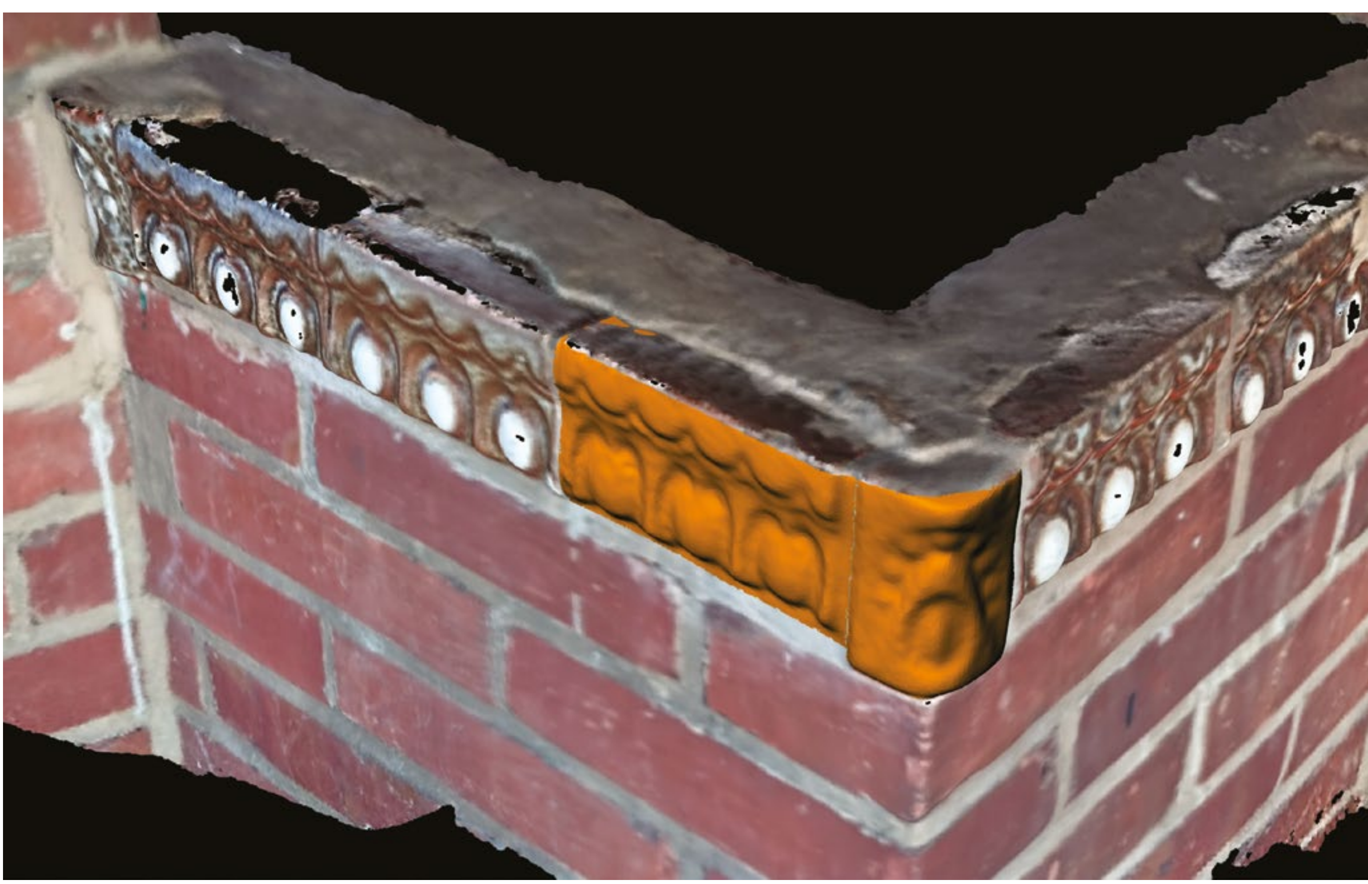

Figure 7: 3D Scan showing damaged historic ornaments from glazed ceramics. Replacements marked orange.

the required actions to produce and post-process them. With such components already being used in the complementary manner advised for AM ceramic components, this criteria may be seen as fulfilled. As the high relevance of preserving, maintaining and restoring historic buildings may be assumed as common sense, the author prefers to refrain from a discussion on the economic point of view.

CONCLUSION

Based on the three examples mentioned, it is apparent that the use of functionalized AM ceramics in architecture is generally well feasible. Yet, only low-tech approaches have been undertaken, which is due to the rather low resolution, as well as the relatively high tolerances inherent to the process of Robocasting.

Depending on the desired outcome, several strategies to achieve greater geometric freedom or harmonize surface-qualities are available. Together with optimizations regarding print-parameters, as i.e. the resolution, or a geometry's orientation during fabrication, a process of "design for additive manufacturing" is advised.

From an economic view on the topic, the use of AM ceramic components is recommended to be carried out in a complementary manner, combining them with mainly conventionally produced pieces.

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