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The business case for 3D printing in the built environment

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ABSTRACT: Additive manufacturing has matured from a method for prototyping and the fabrication of small, individualized parts to a technology that allows for 3D printing at the scale of buildings. However, the largest inhibitor for its application in the built environment remains the business case. Using the example of nesting bricks that can be integrated into clinker brick facades, the present work explores necessary conditions for the economic use of 3D printing in the construction context. We show that business cases for additive manufacturing in the build environment exist and analyze the technology's potential to scale processes that require intense manual work into industrialized fabrication.

1 INTRODUCTION

While additive manufacturing offers unprecedented freedom of design, and a remarkable potential for material efficiency and lightweight structures, it rarely surpasses stages of art, design, or feasibility studies, let alone finds its way into mass production. Compelling reason for this is that the benefits of the technology – one-off solutions, specific designs, tailored machinery – make it particularly expensive. Hence, regardless of its vast number of advantages, engineers and product designers struggle to define business cases for the technology. The present work investigates the ingredients that are necessary for a successful industrial application of additive manufacturing in the building sector. For this purpose, we study the case of printed ceramics.

Since William Urschel's patent of a *Machine for Building Walls* in the 1930's, additive manufacturing in the built environment has evolved as a tool for product design and prototyping, and has now even reached the scale of entire buildings. Compared to traditional industrial manufacturing technologies such as milling or casting, it offers several advantages. Depending on whether and how many support structures are needed, little to no waste is generated during production (Jiang et al. 2018). Complex geometries with undercuts or cavities can be produced with virtually no increase in production cost: complexity comes for free. The implementation of complex motion controls has unlocked additional degrees of freedom. In this way, the print quality has improved significantly from both a mechanical and an aesthetic point of view (Jiang et al. 2021). New degrees of freedom, of course, necessitated new algorithms for path planning (Jiang & Ma 2020). While dimensions and available materials of 3D-printed components were still limited in the early days of the technology, technical progress has unlocked large formats from a wide variety of materials (Izard et al. 2017). Recent attempts even aimed at replacing the conventional layer-by-layer with a multilayer printing process to reduce the manufacturing time (Jiang 2020). All these developments have matured additive technologies to scales of the construction industry, which, by nature, has a need for large-format and, above all, individualized components (Kloft et al. 2021).

Applications in the built environment extend from highly specialized interconnecting nodes for free-form facades (Mohsen 2020) to shape-optimized, large-format components made of reinforced concrete that offer the potential of more sustainable construction through the efficient and economic use of resources (Kloft et al. 2020). Additive manufacturing techniques used in the construction sector are unique with respect to both the material used and the technology applied in each case

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(Al Rashid et al. 2020). In addition to the typical off-site production (factory or lab), there are examples of on-site printed large structures, such as a wire-arc additively manufactured steel pedestrian bridge on the campus of the Technical University of Darmstadt (Feucht et al. 2020), or an apartment building built in Beckum, Germany (PERI GmbH 2020, 2021). In addition to terrestrial applications, additive manufacturing is considered for the construction of extra-terrestrial colonies. The space industry aims at using lunar or Martian dust and rock for the construction of permanently inhabited stations (Cesaretti et al. 2014).

These technological developments fall into a time where we witness a shortage in building materials and increasing costs for construction and the disposal of waste; a time where discussions on the environmental impact of technologies have arrived at architecture and construction. The established notion of cheap construction materials and expensive geometric complexity seems outdated. Instead, complex components that integrate several functions and transfer loads efficiently are becoming important. Yet, the largest inhibitor for the application of additive manufacturing in the built environment remains the business case.

In recent years, additive manufacturing has found its way into many industrial sectors, including the built environment. Today, almost all classes of materials (metals, plastics, ceramics, biomaterials, etc.) can be used in 3D printers. In general, a distinction between 3D printing processes with powder, molten materials, or liquid materials can be made. Among them, material extrusion is the most common process, in particular for building applications. It is typically used for fusible and pasty materials (e.g., ceramic pastes of clay or concrete). Here, a moldable mass is forced through a nozzle and a uniform strand of material is printed layer by layer on a flat surface by a movable nozzle head to form the desired shape. In the construction sector, the focus has been primarily on 3D printing of concrete. Practical examples demonstrate that entire houses can printed from concrete using the extrusion processes (PERI GmbH 2020, 2021). More recently, first experiments have also been made with clay (Chan et al. 2020).

The present work explores necessary conditions for the economic use of 3D printing in the construction context at the example of printed brickwork.

2 PRINTED CERAMICS: A NESTING BRICK

Owing to their many useful properties (non-combustible, readily recyclable, moisture-regulating, among others), the use of ceramic building materials goes back thousands of years. In addition to classic bricks or roof tiles, products made of fired clay are used as floor and wall coverings, bathroom ceramics, or facade ornaments. Brickwork buildings account for approximately 30% of newly constructed residential buildings (German Federal Statistical Office 2018).

In Germany, the use of visible ceramic brickwork – known as clinker bricks – has been widespread for centuries and still enjoys great popularity today, often in prestigious public or commercial buildings, but also in upscale and high-priced residential construction. Especially in northern and northwestern Germany, unrendered brickwork facades are characteristic of the townscape of small and medium-sized communities and cities. Its resistance to environmental influences and its versatility in terms of building design have made clinker bricks popular products for civil engineers and architects. This is reflected in movements, such as *brick Gothic* or *brick Expressionism*. In 2019, the German brick industry served both national and international markets and generated sales of EUR 183 million in the visible brick sector (Federal Association of the German Brick and Tile Industry 2019).

Owing to its extrusion process, shapes of today's industrial brick production are limited to cuboid and uniform products. Special formats are produced only upon customer request and in an elaborate manual process (Figure 1). These custom-made products not only require extensive human resources, but they cause enormous amounts of waste in production (often up to 80%). Because of their complex shape, custom bricks commonly feature special drying and firing properties. As a result, often cracks develop in the drying and firing process, rendering the bricks unusable.

A frequent problem in renovations of existing buildings, but also in new buildings, is a potential loss of habitat for birds and bats due to the construction measures. Building owners are therefore

Figure 1. Manual fabrication of nesting clinker bricks at?.

often obliged by the responsible authorities to compensate for this loss of habitat through suitable measures – so-called species protection compensation measures – by installing suitable nesting facilities on the facade. Such nesting boxes are equally unpopular with building owners and planners, as they impair the appearance of the facade significantly. So-called nesting bricks offer the possibility of a complete integration of nesting space into the brick facade combining aspects of species protection and aesthetics.

Nesting bricks are customary masonry bricks equipped with nesting cavities for endangered species (Figure 2). The product allows for the compensation of habitat losses caused by demolition or reconstruction, or even the generation of additional habitats in new buildings. The current production of nesting bricks is a laborious, manual process with a correspondingly low yield of less than 100 pieces per year at a representative manufacturer. It begins with hollowing out of a solid block of clay and requires the manual modeling of protruding parts such as a canopy over the bird entrance hole (Figure 1). The manual fabrication of a green body takes an average of two working days for a trained ceramics technician – a profession that is not taught anymore. Even small numbers of rejected (cracked) pieces in the production process cause high costs.

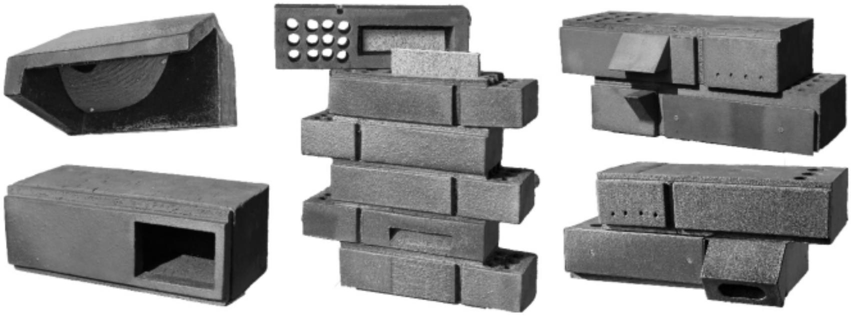

Figure 2. Examples of nesting bricks manually produced by a representative manufacturer?.

The additive manufacturing of ceramic products allows for the transfer of this manual manufacturing process to industrial production. Using 3D printing, it is possible to automate and standardize the production of customized special-purpose bricks. This allows for the scaling of production (number of bricks produced) and for a significant expansion of the product range (number of variants offered). The latter is currently inhibited because of high costs of the manufacturing process caused by the necessary high labor and material inputs. The issue is further complicated by a scarcity of workforce trained in the highly specialized field of molded brick production.

3 THE ADDITIVE MANUFACTURING BUSINESS CASE

Ceramic 3D printing has been used in a wide variety of processes since the beginning of the millennium, but has concentrated mainly on technical (medical, electrical or mechanical engineering) applications (Chen et al. 2019). In construction, this technology has been experimented with since the mid-2010s. Here, the process of choice is robocasting (Chan et al. 2020), since other processes only allow for small-format components. Projects are thus far rather artistic, such as pavilions and installations. An industrial application of the technology for a marketable series product has not yet taken place (Wolf et al. 2022).

Investigated the industrial potential of the technology using a 6-axis robot arm and a selfdeveloped conveyor system for the clay mass (Figure 3, top left). They demonstrated the possibility of an industrial fabrication of hollow bricks (Figure 3, top right) and functional infill patterns (Figure 3, bottom) and, hence, provide the technological basis for the automated production of nesting bricks.

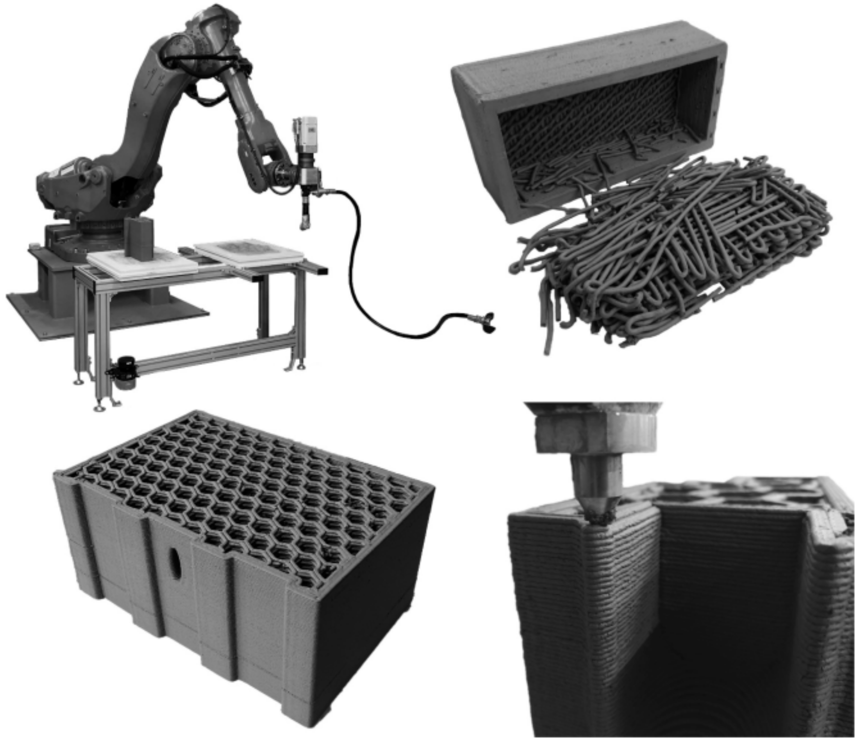

Figure 3. Brick printing at TU Darmstadt: 6-axis robot with conveyor system (top left), removable support material (top right), and functional infill patterns (bottom).

The currently limited manual production capacity of a typical clinker brick supplier of less than 100 nesting clinker units per year corresponds to a market share for nesting boxes of less than 2%. The use of additive technologies would allow for increasing this capacity to about 1,000 nesting brick units per year. This corresponds to a market share of about 20% in the market segment of planning-relevant species. Since producers of nesting bricks that can be integrated directly into facades are extremely rare, a high double-digit market share for this special product can be achieved. As a consequence building owners and planners, who value a complete integration of the nesting possibilities into the clinker brick facade, would have to fall back on clinker bricks from the product portfolio of our exemplary manufacturer for the facade design. Only their facade clinker bricks would be completely optically adapted to the nesting bricks, which generates additional sales.

Using the example of a clinker brick supplier that serves approximately 4000 projects yearly, we estimate that the unique selling proposition of additively manufactured nesting bricks will allow for the acquisition of 100 additional projects per year. This very conservative estimation of the expected revenue potential corresponds to an increase of sales of 2.5%. With approximately 13,000 clinker units installed per project, this corresponds to an increase in sales of EUR 850,000. As awareness of the product will increase over time, this number is expected to increase.

Even outside of species protection obligations, new, additional customers who value biodiversity and aesthetics at the same time can be won with the argument of promoting biodiversity, allowing for a positioning in the market as a sustainable, future-oriented company. Additive manufacturing technologies are not yet widespread in the brick industry. This pioneering case would allow for taking the innovation leadership in the field. In addition, a successful implementation enables the industrial fabrication of other customized, hand-made brick formats and special-purpose bricks such as mailboxes.

4 CONCLUSIONS

Additive manufacturing has matured from a method for prototyping and the fabrication of small, individualized parts to a technology that allows for 3D printing at the scale of buildings. However, harnessing its potentials requires the identification of cases where all of its strengths are at play. Using the example of nesting bricks that can be integrated into clinker brick facades, we have shown that business cases for additive manufacturing in the build environment exist. Not only has it the potential to scale manual work into industrial processes, but it offers the possibility of capturing entire (new) markets.

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