Mechanik, Werkstoffe und Konstruktion im Bauwesen | Band 62

Dennis de Witte

Clay Printing

The Fourth Generation Brickwork

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Mechanik, Werkstoffe und Konstruktion im Bauwesen

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Dedicated to the memory of

Karel de Witte,

Your continuous support was instrumental.

Figure A.1 Printed and standard bricks

Abstract

The built environment has been using clay-based products for centuries. Most bricks are made from local materials, and the production processes are usually based on extrusion and simple moulding processes. Over time, they were optimised to produce products with a constant quality. Additive Manufacturing (AM) is not widely used within the built environment yet, but utilising AM to produce free-form (structural) silicate ceramic (clay) building components that do not need to be produced in large batch sizes was a motivation to investigate the possibilities that the application of AM offers to process clay.

The research described in this thesis focusses on the production and use of AM-produced clay products for the built environment. The research is limited to clay materials which are used in the brick industry. It is characteristic for these materials that they are silicate-based, and often use a form of chamotte for green strength and to reduce shrinkage. Part of the research was to look at what type of clay building products can be made and which AM principle can address the design related demands.

When this research was initiated, only small art objects were printed in clay. To start the research and to assess the potential of AM for clay within the built environment, a desktop printer based on a robocasting process was used. The first promising test specimens were printed, but some flaws were observed. These flaws were reported and used as input to develop a new printer. While building components are generally larger than most additively manufactured products for industrial application, with the development of a new machine, the print volume for the realised products had to be increased and the print time had to be reduced. After comparing the AM categories and technologies, the initiated design of a machine to improve the processing of clay was based on robocasting. This decision was taken based on the performance of the predefined conditions and demands, whereby the material, the print speed, and the structural performance were important parameters. The methodology used to improve the print process was based on defining the demand with a design study in order to derive the specific conditions that need to be met by the new printing process. Besides deriving the demands, reverse engineering took place on the desktop printer to understand the printing process, and background research was conducted on silicate ceramics used in the built environment in general.

To facilitate replicability, a new extrusion mechanism was designed. The extruder was attached to a robotic arm to facilitate the print of larger objects. A visual examination of the printed parts was carried out as well as structural tests to assess the performance.

The outcome of the research is an extrusion mechanism that can print a relatively

liquid clay paste in the desired geometry. Only one material could be printed with the realised robocasting printing technology. Therefore support structures or large cantilever overhangs were not printed yet, which limited the freedom in form during the research trajectory. The technology improved compared to the first desktop printer, but has to be further optimised to print all the designs that had been drawn up in order to define the conditions and specifications for the machine's layout.

A future vision shows a roadmap that indicates future development. For application in the built environment, certification is an important criteria. Therefore, further improvement and process certification are the next steps to implement printed clay parts in the built environment.

Abstract Deutsch

Auf Lehm basierte Produkte werden bereits seit Jahrhunderten in der gebauten Umgebung verwendet. Die meisten Backsteine oder Ziegel werden aus lokal verfügbaren Materialien hergestellt und die Fertigungsprozesse basieren meist auf Extrusion und einfachem Formpressen. Im Laufe der Zeit wurden diese Prozesse optimiert, um eine gleichbleibende Qualität der Produkte sicherzustellen. Additive Manufacturing (AM) ist im Bau bisher nicht weitverbreitet, aber die Verwendung von AM zur Fertigung von freigeformten (konstruktiven) Baukomponenten aus Silicatkeramik (Lehm), die nicht in hohen Zahlen gefertigt werden, war eine der Motivationen, die Möglichkeiten zu untersuchen, die die Anwendung von AM mit Lehm bieten kann.

Die in dieser Arbeit beschriebene Forschung konzentriert sich auf die Produktion und die Verwendung von AM-gefertigten Lehmprodukten im Bau. Die Arbeit beschränkt sich auf Silicatkeramikmaterialien, die in der Ziegelfertigung verwendet werden. Zu den typischen Eigenschaften dieser Materialien gehört, dass sie auf Silikat basieren und oft mit Schamotte angereichert sind, um die Grünfestigkeit zu gewährleisten und Schrumpfung zu reduzieren. Ein Teil der Forschungsarbeit befasst sich damit, herauszufinden, welche Art von Lehmbauprodukten hergestellt werden können und welches AM-Prinzip den entsprechenden Anforderungen am besten entspricht.

Zu der Zeit, als diese Forschungsarbeit begonnen wurde, wurden nur kleine Kunstobjekte aus Silicatkeramik gefertigt. Zu Beginn der Arbeit wurde ein auf einem Robocasting-Prozess basierender Tischgerätdrucker benutzt, um das Potenzial von AM mit Silicatkeramik für den Bau zu bewerten. Erste vielversprechende Muster wurden gedruckt, allerdings wurden dabei auch Schwachstellen beobachtet. Diese Schwachstellen wurden protokolliert und als Eingangskriterien für die Entwicklung eines neuen Druckers verwendet. Da Bauprodukte im Allgemeinen größer sind als die meisten anderen AM-gefertigten Teile zur industriellen Anwendung, sollte bei der Entwicklung eines neuen Druckers das Druckvolumen erhöht und die Druckzeit verringert werden. Nach einem Vergleich der verschiedenen AM-Kategorien und -technologien in Bezug auf eine Verbesserung der Verarbeitung von Silicatkeramikprodukten sollte ein auf Robocasting basierendes Gerät entwickelt werden. Diese Entscheidung basierte auf der Leistungsfähigkeit der vordefinierten Bedingungen und Anforderungen. Dabei waren Material, Druckgeschwindigkeit und Strukturfestigkeit wichtige Parameter. Der Methode, die zur Verbesserung des Druckprozesses angewendet wurde, lag die Festlegung

von Anordnungen aus einer Design-Studie zugrunde, die die spezifischen Bedingungen herausstellte, die ein neuer Druckprozess erfüllen muss. Neben der Herausarbeitung der Anforderungen wurde an dem ursprünglichen Tischgerätdrucker Reverse Engineering durchgeführt, um den Druckprozess genau zu verstehen. Daneben wurden Silicatkeramiken für Bauprodukte im Allgemeinen untersucht.

Um eine Wiederholbarkeit zu fördern, wurde ein neuartiger Extrusionsmechanismus entworfen. Der Extruder wurde auf einem Roboterarm montiert, um das Drucken größerer Objekte zu ermöglichen. Danach wurden die gedruckten Teile visuell inspiziert und auf ihre konstruktive Belastbarkeit hin getestet.

Das Ergebnis der Forschungsarbeit ist ein Extrusionsmechanismus, mit dem eine relativ flüssige Lehmpaste in der gewünschten Form gedruckt werden kann. Mit der hierbei realisierten Robocasting-Drucktechnologie konnte nur ein Material verarbeitet werden. Daher wurden auch noch keine Unterstützungsstrukturen gedruckt, was die Formenfreiheit insofern eingeschränkte, dass keine großen Überhänge verwirklicht werden konnten. Die Technologie wurde gegenüber dem ersten Drucker verbessert, muss aber weiter optimiert werden, um alle Entwürfe drucken zu können, die als Bedingungen und Spezifikationen für das Drucksystem gestellt wurden.

Der Blick in die Zukunft wird mit einer Roadmap dargestellt, die zukünftige Forschungsthemen aufweist. Für die Anwendung der Technologie in der gebauten Umgebung ist die Zertifizierung ein äußerst wichtiges Kriterium. Daher sind Druckerverbesserungen und eine Prozesszertifizierung die nächsten Schritte für eine Implementierung von gedruckten Silicatkeramikprodukten.

Abstract Nederlands

Sinds jaren wordt klei gebruikt voor bouwproducten. De meeste stenen worden gemaakt uit lokaal gewonnen materialen. De toegepaste productieprocessen om deze te maken zijn vaak gebaseerd op extrusie en dat van gieten. Deze zijn geoptimaliseerd om producten met een constante kwaliteit te kunnen produceren. Additive Manufacturing (AM, ook wel 3D printen genoemd) wordt nog niet vaak in de bouw gebruikt, maar de mogelijkheden die deze techniek biedt om van silicaat keramiek (klei) producten met een vrije vorm te maken, zonder dat deze in grote seriegroottes geproduceerd moeten worden, is een motivatie om de mogelijkheden daarvan te onderzoeken.

Het onderzoek focust zich op de productie van een AM-productieproces en de producten die daarmee gemaakt kunnen worden. Het onderzoek reduceert zich tot silicaat keramiek, welk ook in de bouw toegepast wordt. Kenmerkend voor de toegepaste materialen is dat ze op silicaatachtige keramieksoorten gebaseerd zijn en dat er vaak een vorm van chamotte in verwerkt is voor een zekere groene sterkte en om krimp te reduceren. In het onderzoek wordt gekeken welke producten kunnen worden gemaakt met deze additieve techniek en welk productieprincipe de juiste producteigenschappen zouden kunnen hebben om voorgenoemde producten te maken.

Aan het begin van het onderzoekstraject werden alleen kleine keramiekobjecten geprint. Om het onderzoek op te starten en de potentie van het printen te beoordelen, is een kleine printer op basis van een zogenaamde robocasting techniek gebruikt. De eerste veelbelovende onderdelen konden daarmee geprint worden, maar ook werden enige gebreken zichtbaar. Deze gebreken zijn bijgehouden en gebruikt bij het ontwerp van de nieuw te ontwikkelen printer.

Omdat gebouwcomponenten groter zijn dan de meeste geprinte producten voor overige industriële toepassingen, moest het printvolume vergroot worden en de printtijd gereduceerd. Robocasting werd aan de hand van een procesvergelijk gekozen als proces voor de nieuwe printer. Daarin waren het te printen materiaal, de printsnelheid en sterkte van de geprinte onderdelen belangrijke parameters. De methodiek die gebruikt is, is gebaseerd op het formuleren van eisen aan de hand van een ontwerpstudie, die daarmee de prestaties van de nieuwe printer definiëren. Naast het afleiden van de eisen, is er door middel van reverse engineering onderzocht hoe de kleine printer functioneert. Daarnaast is er onderzoek gedaan naar het gebruik van keramiek in de bouw.

Om de reproduceerbaarheid van de producten te garanderen is er een nieuw extrusie mechanisme ontworpen. Dit mechanisme is aan een robotarm gekoppeld, om daarmee

grotere objecten te kunnen printen. Om de prestatie te beoordelen, zijn de geprinte objecten visueel geïnspecteerd en beoordeeld. Ook zijn er sterktetests gedaan.

Het resultaat van het onderzoek is een printmechanisme dat een relatief hoog viscoos materiaal in een gewenste vrije vorm kan printen. Het betreft een techniek die eveneens in de categorie robocasting valt. Momenteel kan er nog maar met één materiaal geprint worden en zijn er nog geen zogenaamde steunmaterialen geprint. Dit limiteert de vrijheid in vorm, daar grotere uitkragingen nog niet gerealiseerd kunnen worden. De printtechniek is ten opzichte van de eerste printer verbeterd, maar zal nog moeten worden geoptimaliseerd om ook daadwerkelijk alle ontwerpen, die waren gemaakt om de uitgangspunten voor een nieuwe printer te definiëren, goed te kunnen printen.

Een strategie die de toekomstige ontwikkelingen weergeeft wordt besproken in het laatste deel, waar de toekomstige ontwikkeling centraal staat. Certificering van producten voor de toepassing in de bouw is belangrijk. Daarom zijn de verdere ontwikkeling van de printtechniek en certificering de belangrijkste vervolgstappen die genomen moeten worden om geprinte keramiek onderdelen in de bouw toe te kunnen passen.

Preface

Additive Manufacturing (AM) is a technology that facilitates realising products by selective placement of material in subsequent layers. It is a technology that emerged in the 1980's and has been adopted by many industries for prototyping and the realisation of special or individualised products, which cannot be made by use of common production processes or benefit economically by the use of AM. Therefore, AM is a technology that stands besides traditional processes such as subtractive manufacturing and moulding (Figure A.2).

The building industry relies on building principles that are a result of local building traditions and building codes. This, combined with a high degree of individualisation compared to the mass production seen in other industries, differentiates the building industry from other industries. The desired lifespan differs from consumer products that are mass produced, too. Therefore, "disruptive" innovations as AM are not implemented instantaneously. This seems the reason why AM has not been widely utilised in the built environment.

Fascinated by the technology, I analysed the AM processes utilised to process concrete during my Master's study at the Master's track in Building Technology at the Faculty of Architecture and the Built Environment at TU Delft. Contrary to many materials used for AM, concrete is a composite that solidifies due to a chemical reaction, which is initiated when the material is mixed. The reaction speed can be controlled by use of accelerators. The accelerators can be added just before extrusion but due to the initiated chemical reaction in the material, a continuous extrusion process is desired to control the material during the printing process. Even though the technology has evolved over the last years, the chemical reaction related to mixing concrete was not sufficiently changed to be used in the AM process.

At the same time, artists started to experiment with printing silicate ceramics (clay). This material is widely used in the built environment and AM could be used to make free-form clay building parts. Compared to concrete, clay seemed to have better characteristics to be shaped with an AM process. While concrete solidifies by a chemical reaction, clay will solidify by drying. After drying, the chemical reaction takes place when the shaped green body is fired. While the shaping and final chemical reaction, which give fired clay products their final strength, happen at different points in the production process, AM can be used for just the shaping within the complete production process of free-form bricks (de Witte, D., 2015).

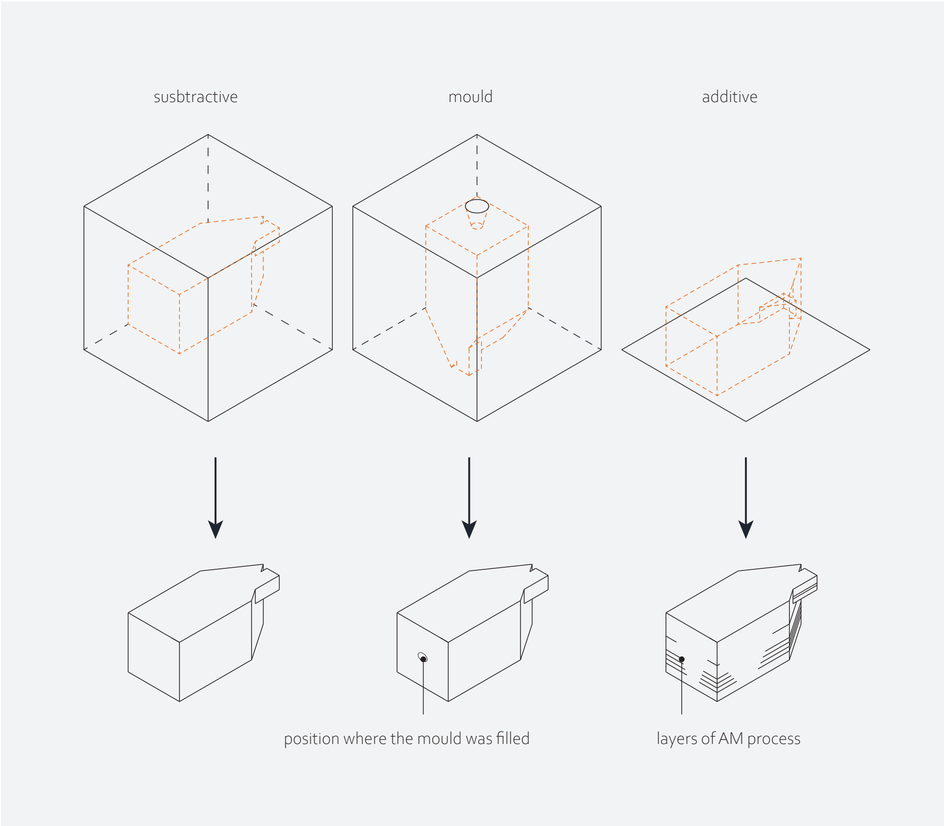

Figure A.2 Subtractive manufacturing, moulding, and Additive Manufacturing
Three main production processes show how a product can be made. With subtractive technologies, material is removed by milling, for example. Moulding uses a liquid material and formwork. AM uses just the raw material and reduces the amount of lost material.

In 2015, this research on how AM could be used for clay building components was initiated at TU Darmstadt. The outcome of a comparison between building materials made with an AM technology and the aforementioned concrete showed that clay is a material that could be printed and processed with respect to the material's characteristics. It was the motivation behind this research, since there was neither research on printing (load-bearing) clay building components, nor well documented characteristics of clay for processing with an AM process. The challenge of the research was to search for an adequate technology that was able to produce the desired clay products for the built environment. This involved understanding the seven main AM types, as well as the material characteristics in relation to a production process. After the research started it became clear that clay could be post-processed more easily than other materials. It is, for example, possible to improve the surface quality of additively manufactured clay parts between the different production steps, by use of milling. The material milled from the print can be reused easily by mixing it with new material, which is not always possible with other materials. Although a life cycle assessment is not part of the research's scope, lower environmental impact of the production process is an important benefit that cannot be neglected.

Over decades, the brick industry has invested to improve the performance of the brick and the efficiency of the production technology. Printed bricks are the fourth generation of bricks. After dried, fired, and insulating bricks, free-form bricks made with AM can provide a geometric form freedom while using a durable building material.

This research shows a broad overview of AM for clay. It describes the evolution of brickmaking, how clay building products can benefit from an AM process, which production process could meet the defined demands regarding the final product, which characteristics the prints have, and what topics could or should be addressed in future research.

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Part I

The first part of the thesis discusses the background of Additive Manufacturing (AM) and brickmaking. As AM has not yet been utilised for silicate ceramics (clay), building components made with state of the art brickmaking technologies are shown. In addition to the relatively traditional process technologies for clay materials, the seven AM categories – in which almost all AM technologies can be categorised – are discussed. After a general introduction to the processing technologies, the research questions are defined.

Figure 1.1 Brickwork buildings
Front street, New York, USA

1 Towards the fourth generation brickwork

Additive Manufacturing (AM) is one of the new developments in the building industry. While many building components are highly standardised in form and dimension, AM can provide individualisation of many products.

Brickwork is one of the oldest building materials. Over the years, the material for clay building products and the production process have been adapted to each other. In addition to improvements in quality and quality control, the up-scaling and optimisation of the production processes lead to more standardised products. The standardisation has an economic benefit because it caused bricks to become cheaper, but this also means that, with brickwork, the labour costs are higher than the actual material costs. Producing brickwork is less individualised in the built environment (Mulder, K., 2016, pp. 3-5), and stretcher bond masonries are the most cost-effective regarding labour costs. The human scale is beginning to be missing in many designs, while the price difference between standardised and individualised products has increased. Together with an architectural trend towards brutalism and modernism, which include fewer ornamental clay ceramic details, the individual components and appearance of buildings decreased.

Fascinated by architecture, brickwork, engineering, and innovative production processes, this research focusses on how AM can be adapted, utilised, and implemented to provide the building industry with completely individualised clay building components.

Over centuries and especially over the last decades, the production technologies and performance of the building components underwent extensive optimisation. In addition, new technologies have been invented. These inventions do not only relate to clay products, but rather to many other materials that are processed with optimised technologies. However, local building traditions play a significant role in a construction's structural composition. Depending on the building system used, the way the products and technologies are optimised differ. And although the building tradition of many countries differ, the energy crisis has led to innovative solutions with respect to local building traditions. The local types of building structures have been adapted to fulfil the demand. As a result, the different structural system layouts exist as substitutes and they respond to the different building traditions. However, the solutions are not complete substitutes, since in these traditions, solutions to cope with local environmental situations are embedded as well.

AM is one of the last and more disruptive inventions introduced to the built environment. The last industrial revolution is indicated as the smart industry, also known as Industry 4.0. Hereby, automation with a "smart" exchange of data between the fabrication

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Figure 1.2 Brickwork residential buildings
Utrecht city centre with the Dom’s brickwork tower in the background - Utrecht, the Netherlands

processes leads to more efficient production processes.

AM was developed during the third industrial revolution and the first AM technologies were already described and started to emerge in the late seventies and eighties of the last century. Hereby, digitalisation and robotics played an important role. Decades after AM was invented and used in other industries, the generally conservative building industry started to draw up scenarios of what AM could be utilised for by around 2010-2015. The research analyses production methods, materials, and fabricated products to determine how they can be adapted for AM. Before the analysis, the definition of AM must be described. AM, also referred to as 3D printing, is a relatively new production technology, which has been adapted for different materials. 3D printing can also refer to a specific technology based on binder jetting technologies within an AM category. To prevent confusion, in this research, 3D printing will indicate this specific technology and not the production category AM.

Additively manufactured parts widely used for prototypes and consumer products fulfil different conditions. Therefore, the application and materials differ, but all developed technologies rely on seven processing principles as categorised in ISO/ASTM 52900 which replaces ASTM F2792a-12a.

In the built environment, where almost every building is individualised, a process that can produce any shape or form without additional costs for e.g. formwork is desirable. However, the production process needs to be flawless before products can be utilised in the built environment. The scale of the individual parts used in construction exceeds the building volume of many desktop and industrial AM machines, and the materials used in the construction industry differ from many engineering materials. Clay has been used as a building material over millennia, serving as structural and decorative elements. In contrast to the material categories of metals and polymers, ceramic additive manufacturing processes are less readily available, which is especially true for classic ceramics like clay. To meet the conditions for free-form clay building parts, the process needs to be adapted to be able to produce the desired geometrical forms, process the classic ceramics, and guarantee replicability.

1.1 AM for the built environment

AM is utilised in many industries and adapted to their specific needs. To use AM for building components, the scale of AM has to be adapted. Considering that the majority of building components are stacked on each other, a brief comparison of common manufacturing processes in the built environment and additive manufacturing can be made. Additive manufacturing is defined as shaping an object by selective material deposition at predefined coordinates, next to and on top of each other. The definition of AM utilised in the built environment is discussed here to define the interpretation of these layers and the scope of the research.

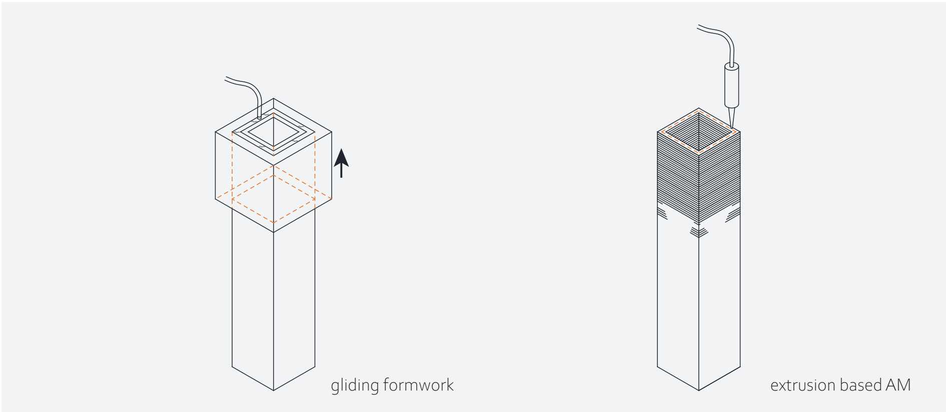

Figure 1.3 Comparison of gliding formwork and AM
Note that there is a difference between gliding and climbing formwork. Climbing formwork is moved in steps while gliding formwork moves almost continuously.

The terminology of AM is not defined in detail, and there are some nuances regarding the characteristics of what defines an AM technology (Gebhardt, A. & Hötter, J.S., 2016, p. 84). A short explanation of AM would be: “a technology that generates a form by merging material together layer by layer”. However, this definition raises many questions. Especially in the construction industry, where material is often stacked on each other and “merged” together, whether by use of a binder agent, or by pouring material in layers, in formwork, for example.

While there is no proper definition of AM yet, selectively putting material on top of each other, layer by layer, seems the best explanation of AM (Gibson, I., David, W.R. & Stucker, B., 2010, pp. 1-2).

Figure 1.3 shows an abstract sketch of gliding formwork and additive manufacturing. If merging material together layer by layer is AM, than pouring concrete in gliding formwork with short intervals can be considered AM, too. The question is whether this method of processing a material complies with applying layers of material on top of each other to create an object.

Since gliding formwork is not considered AM, other parameters must be determinative. The resolution of gliding formwork can be considered low – due to the scale – as well as high, because the seams are not visible. The process is uninterrupted.

In comparison to concrete with aggregates like pebbles, the highest resolution for additive manufacturing of ceramics is achieved with a very fine ceramic powder or paste, depending on the print technique used, where particles are in a micron range and layer thickness is minimised, or in case of an extrusion technology if the nozzle has a very small diameter. If layer thickness is usually within a few microns, a printer with a 3mm-nozzle would result in “macro scale additive manufacturing”, however still categorised as AM.

The scale on which a process is referred to as printing or as stacking does not seem to

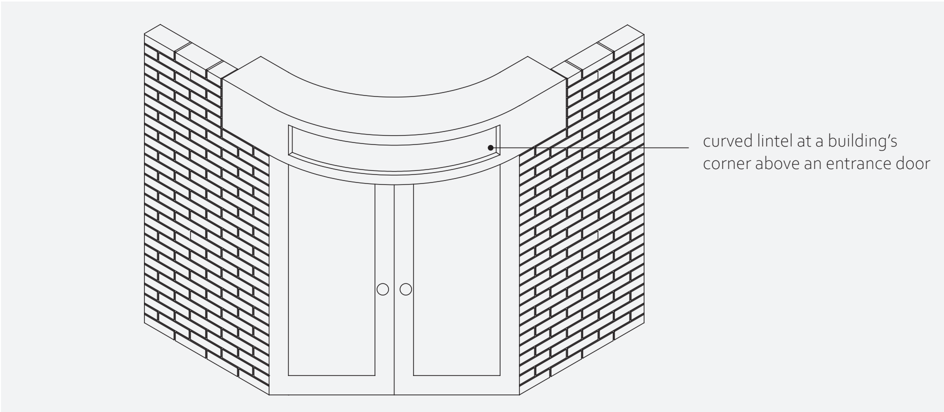

Figure 1.4 Curved lintel

be defined by any current standards. If the size of the base material that forms the product is not defined, and pebbles in concrete could make up the largest parts in an AM process, masonry could be considered AM as well (Pegna,J., 1997, p. 435). The bricks are stacked layer by layer, brick by brick, like voxels by AM. The bricks would be the large aggregates of the structure. Automated stacking of bricks has been demonstrated by Elashry, K. and Glynn, R. (2014).

A single brick, or even larger elements, could be the voxel size and thereby the resolution of the printer. This implies the voxel defines the resolution. But brickwork laying is not considered AM either. Is it caused by the voxel size of the bricks or because bricks are semi-finished products themselves?

Due to the missing definition of the size of the raw material, the question arises if AM should be specified as shaping geometry with a raw material. Bricks are semi-finished products and a brickwork wall is therefore not made by use of AM. Concrete, however, is still a raw material, but (temporary) formwork is needed. The need for prefabricated formwork cannot be adapted easily. Does the dependence on formwork for shaping the material mean that pouring concrete in separate layers is not the same as 3D printing or should the formwork be considered apart from the AM process since it is always prefabricated, i.e. a separate process? Or, on a different note, is the level of automation regarding the positioning of material of any influence to categorise a technology as AM?

So, while many production technologies used at the construction site may be categorised as AM, most of them are not considered AM. The dominant process parameters which determine AM seem to be the use of raw materials instead of semi-finished products, and to build a form following an automated, pre-programmed path. Next to this, AM processes utilise a support material or formwork within the same printing process; often made of the same material, an unbound component of the final material composition, or a secondary material.

The conditions under which a technology is considered AM or not seem hard to define. There is no precise definition, but the before-mentioned criteria regarding material, automated processing, and support material are met by many AM categories defined in ISO/ASTM 52900. There are exceptions to this, e.g. Laminated Object Modelling (LOM). The sheets used in this process are semi-finished products, which are laminated on top of each other.

1.2 Expectations of AM for bricks and brickwork

Although AM becomes more common, there are a variety of technologies that form and are categorised as AM. Each of these technologies has its own advantages and disadvantages. This becomes more complex since there is not one clear definition that formulates what AM is and what underlies that fact. The different processing categories based on ISO/ASTM 52900 within AM are described in Chapter 5 to create a clear overview of the technologies that become widely accepted as AM. The categories are described in a general manner; individual technologies differ, but they share the same material deposition principle as the category they belong to.

It is interesting to see whether AM can be used for bricks and brickwork. Standardised bricks do not come in many different shapes. The main driving force behind that is the up-scaling of the production capacity of bricks by the brickwork factories. Here for, a concession was made on freedom of form. With AM, the same process could be employed to print any kind of brick with any given shape. This allows for individual project-specific bricks that can be embedded in masonry walls. It is possible to print entire walls; it is, however, time-consuming in comparison to the highly automated extrusion processes.

The research focusses on how AM can be used in a beneficial way to produce bricks for brickwork. Printed bricks will be part of "the fourth generation of brickwork" (de Witte, D., & Fehlhaber, T., 2019). After (1) dried clay, (2) fired clay, and (3) insulated, rationalised, higher performance bricks and brickwork structures, the fourth generation, namely free-form, parametric brickwork products can be produced with AM. Figure 1.4 shows a first idea of a brick that could be printed based on the complexity of the geometry. Figure 1.5 shows a brick that does not have a standard rectangular shape but rather a special internal geometry, which accommodates additional functions within the brick. In this specific example the brick can function as a heat exchanger due to the integrated tubes. The principle is demonstrated in concrete at the ETA factory in Darmstadt, Germany (Eberhard, A., Schneider, J., Beck, M. & Maier, A., 2018, p. 38).

These two examples show the potential of new forms and integrated functions in brickwork. It must be investigated whether they can be realised and perform as desired. This research focusses on the print technology and the products. The objective is to investigate: "How structural ceramic components can be produced with an additive manufacturing process to increase the product's functionality within the built environment".

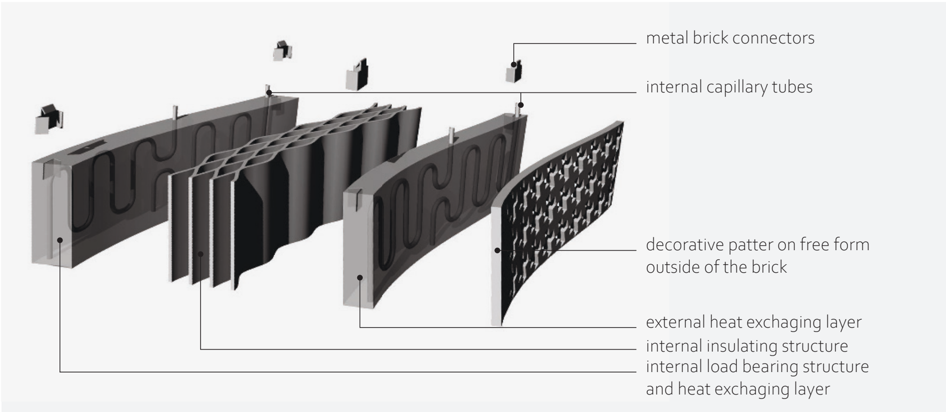

Figure 1.5 Heat exchanging brick

This question and the according sub-questions were formulated since there was neither a detailed working technology available yet that could be used, nor product designs that would benefit from this disruptive technology. While writing this thesis, more studies and researches were initiated and carried out.

1.3 The research

The methodology to investigate the possibilities of AM is based on a brick design study, which, in turn, is based on the conditions to produce them. The machine described in this research has been designed and adapted to the predefined needs.

To define the aforementioned bricks from the study and to define the conditions to produce them are partly based the brick design study that has been carried out. The research is divided into three parts. The outcome and steps of the iterative design process of the AM technology are enumerated, as well as the evolution of the brickwork itself, the production technology related material composition of the clay, the products of the design studies, and their application. The performance of the printing process, the performance of the products produced, and a future outlook show the capability of the production technology and utilisation of the printed products.

Many of the predefined AM categories have one or more technologies that can process ceramics. This is in part influenced by the type of ceramics and depends on the different printing processes available for a particular material. Freeform shaping by a robotic technology adapted and engineered in this research, whereby the material is selectively deposited by extrusion according to the 3D model, is categorised as extrusion-based AM under the name robocasting.

The scope of the performance-related part of the research is limited to the parts printed with the robocasting technology for larger clay components; however, the complete context of AM in the built environment is described and analysed in order to select and demonstrate the choices made in the design trajectory; based, limited, and guided by the research questions. Why the proposed technology is beneficial for the application is addressed in part two of the research. The engineering of the machine, together with the product design studies, from which the conditions for the development of the equipment itself were obtained, are addressed as well.

This research, Clay printing - The fourth generation brickwork, provides a general overview of the aspects related to additive manufacturing of structural and decorative clay components for the built environment.

Figure 2.1 Brickwork building with corner stones
White Hall - London, United Kingdom

2 Ceramics

Clay is a ceramic material, categorised as a silicate ceramic. It is a traditional ceramic and is mainly used in pottery and buildings components. Ceramics in general are used for a wide variety of applications. The composition of many non-silicate ceramics differ from the clay-based ceramics regarding type of material and the purity of the material itself. Examples of other ceramic materials indicated as higher grade ceramics are refractories, glass, and technical ceramics. Higher-grade ceramics, except glass, are rarely used in the built environment. The production technologies to process them share principles with some of the AM technologies. This chapter will discuss the material categories.

2.1 Material categories

Brickwork is composed of bricks made from ceramics. In general, there are three main classifications to divide all materials, viz. metals, ceramics, and polymers. These classifications of materials are based on the material properties. Next to the main categories, there are composites; these materials combine materials of different classifications (Figure 2.2). In addition, there are advanced materials. These advanced materials are known for their enhanced material characteristics but they are composed of the three classic material categories as well and are therefore categorised as a subcategory of composites. Ashby, M. F., Shercliff, H., & Cebon, D. (2007) divide the materials into more categories. They use a categorisation system with six categories, i.e. metals, ceramics, glasses, elas-

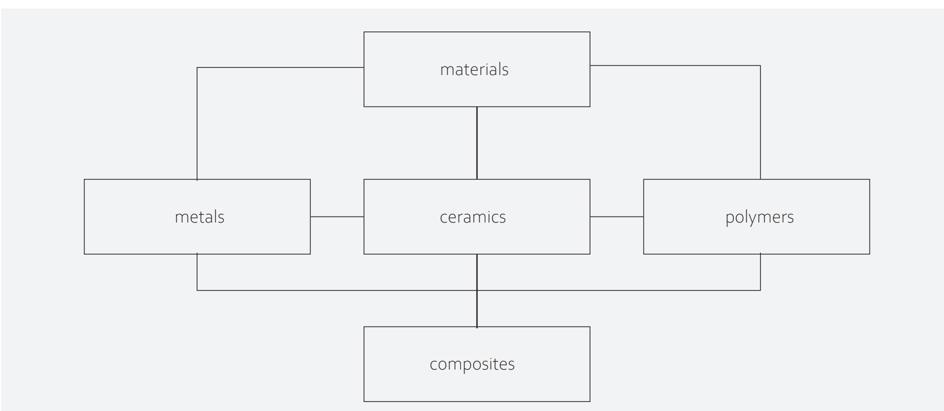

Figure 2.2 Classification of materials

D. de Witte, *Clay Printing*, Mechanik, Werkstoffe und Konstruktion im Bauwesen 62, https://doi.org/10.1007/978-3-658-37161-6_2

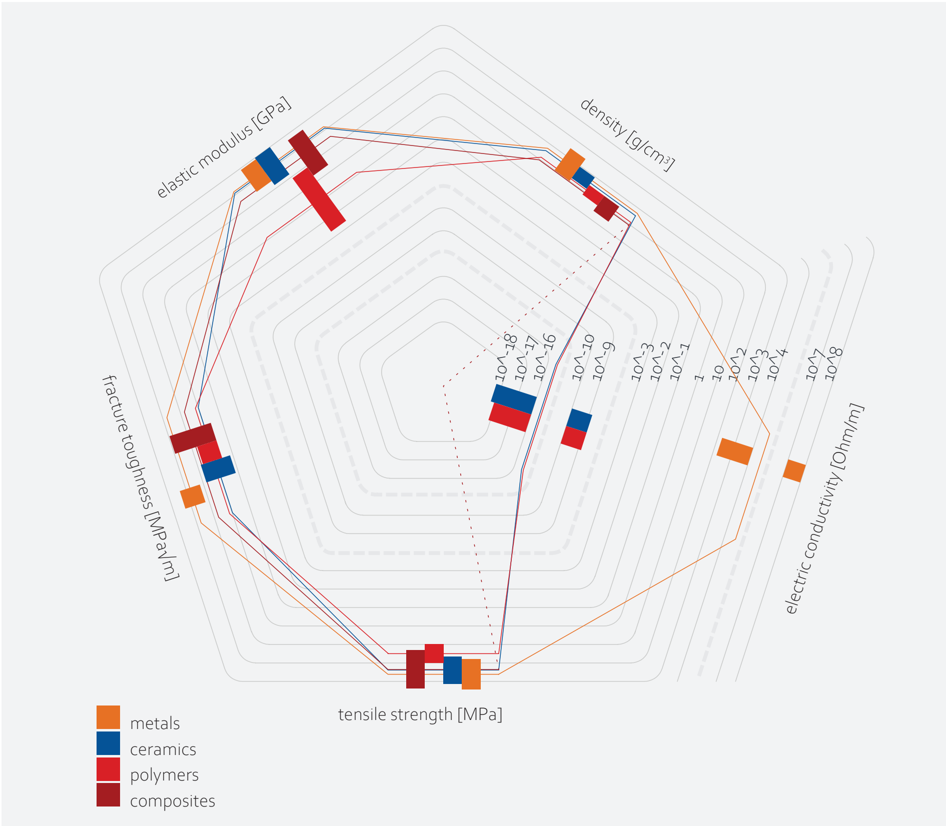

Figure 2.3 Different characteristics of the material groups
Figure based on Callister (2007, pp. 6-8)

tomers, polymers, and composites.

The categorisation shows the relation of materials to other materials. Discrepancies arise between the classification systems when the purpose of categorising changes. Organic materials such as wood and bone could be classified as a composite, since they consist of a matrix and fibre (Saka, S., 1993, p. 1; Piekarski, K., 1973, p. 577). Wood, for example, combines fibre, in this case based around the macromolecular cellulose, and binder (lignin), which together forms the composite. Besides these classifications there are therefore other subcategories that are sometimes considered as a separate category.

The main properties that form the basis of the before mentioned categories are: density, stiffness, strength, fracture toughness, and (electrical) conductivity (Callister, 2007, pp. 5-11). Figure 2.3 shows these different characteristics of the material categories, viz. density (g/cm³), Young's modulus (GPa), tensile strength (MPa), fracture toughness (Kic in MPa·m$^{0.5}$) and electrical conductivity in reciprocal of ohm per meter = mho = σ (S/m).

Figure 2.4 Ruin at the foot of the High Atlas mountain range
High Atlas mountain range, Morocco

Glass can be considered an exception within the ceramics. The non-crystalline material is based on a powdery material like all ceramics, but processed with a special glass production process, whereby the material is heated and melted before it is shaped.

2.2 Ceramics materials

Ceramics are defined by Callister (2007, p. G1) as: “A compound of metallic and non-metallic elements, for which the inter-atomic bounding is predominantly ionic”. Ceramics are categorised between metals and polymers, and they consist of a combination of metallic and non-metallic elements. Examples of ceramics are $Al2O_3$, SiO_2, SiC, Si_3N_4, WC, a refractory ceramic TiC, and clay minerals or materials addressed as classic ceramics. Classic ceramics are e.g. earthenware, stoneware, and porcelain, the latter containing a larger share of kaolinite $Al_2Si_2O_5(OH)_4$, mullite $Al_6Si_2O_{13}$, which can be present as $3Al_2O_32SiO_2$ or $2Al_2O_3$ and SiO_2, and quartz, SiO_2. Cement and glass are considered ceramics as well.

Based on historic categorisation, classic ceramics are all categorised as ceramics. Since porcelain mixtures, for example, also contain the crystalline mullite and quartz, they could be classified as a composite material. Fired classic ceramics are vitrified or semi-vitrified. The amount of vitrification has an influence on the characteristics, for example the water tightness of the fired clay product.

The production process for classic ceramics is generally based on the shaping of the

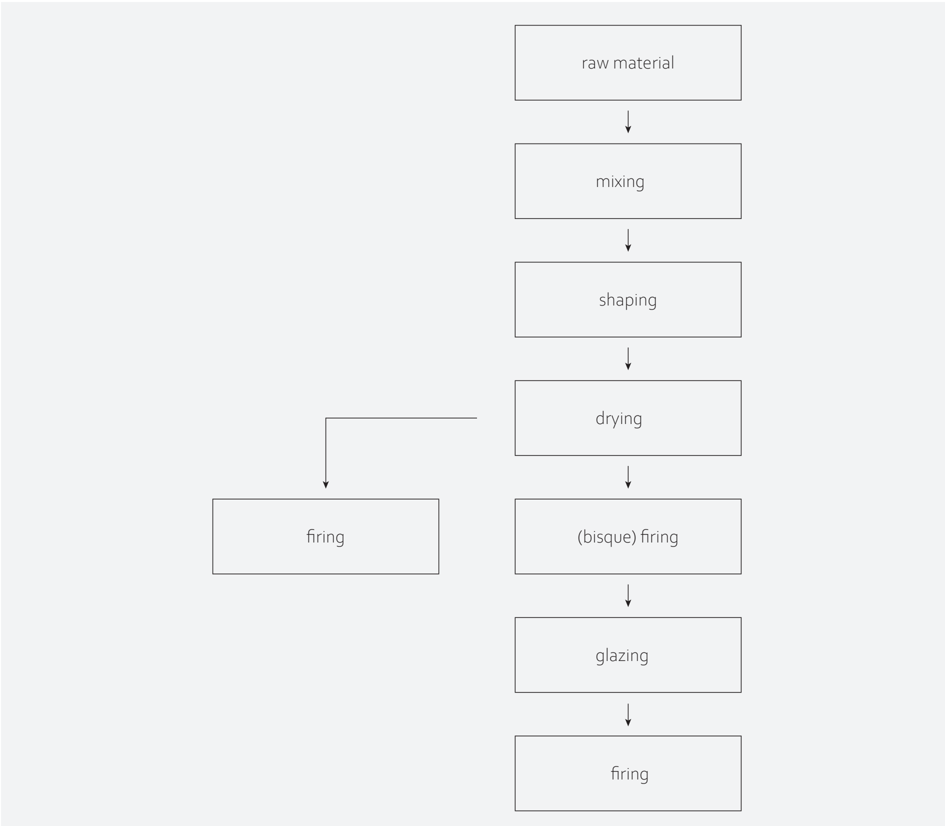

Figure 2.5 General process steps to process ceramic materials

raw pasty material, drying and firing of the green body, where sintering can take place (Carter, C. B. & Norton, M.G., 2013, p. 7; Kollenberg, 2009, p. 522). Figure 2.5 shows the general process steps.

Silicate ceramics are widely used in the built environment. Silica (SiO_2) is the most widely available material on the earth's surface and is found in feldspar, a group of tecto-silicates or framework silicates, and quartz. Although all silicate ceramics are based on silica, the availability differs. Porcelain or bone china are ceramics made from feldspar, kaolin, and bone ash; materials far less readily available. The price of porcelain's raw material is higher, it has different material characteristics and is therefore used in different applications than the cheaper material mixtures, made from wider available materials. An example of a more accessible material is earthenware (also known as terra cotta, from Italian: baked earth), which is made with a lower amount of kaolin and feldspar, but with a higher amount of quartz and ball clay, a material mixture with differing amounts of primarily quartz and kaolin.

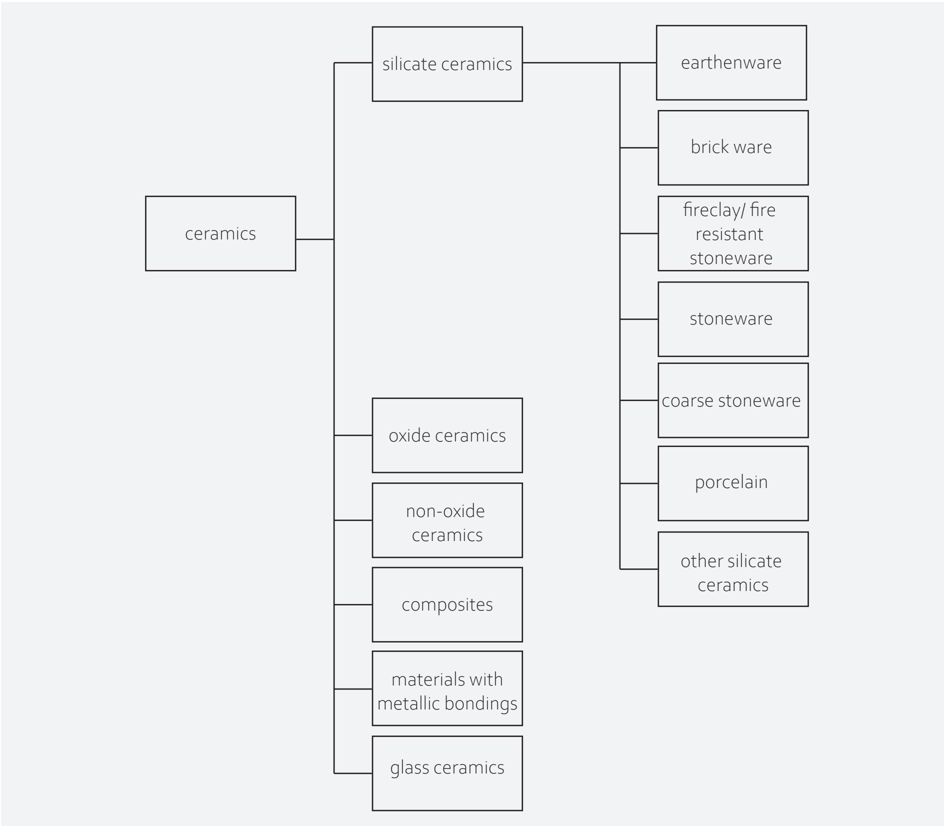

Figure 2.6 Classification of ceramics
(Händle, 2009, pp. 51-53; Roos, W., 2019)

The wide variety of ceramic materials can be categorised by their application. The silicate-based ceramics can be divided in subcategories as shown in Figure 2.6. For brickwork, one of the more widely available materials such as terra cotta is used since there is a large amount of material involved. The size of the products and the according amount of material needed, over the centuries lead to the fact that coarse silicate ceramics are broadly utilised in the built environment. There are products with differing product properties. Therefore, the material is optimised for the product and production process, but the internal geometry also facilitates a variety of products with differing properties. The coarse materials with a particle size larger than 100/200 µm (microns) are used for brickwork products. An exception are rooftiles. The material used here is finer (particles smaller than 100/200 µm) (Roos, W., 2019).

2.3 Processing methods for ceramics

Production processes, in general, can be organised in categories as well. These categories start with a raw material, and are primarily divided into shaping, secondary processing, and a last step, which often comprises joining and surface treatments before the finished product is achieved. Raw materials are often defined as materials found in nature. Raw materials can, therefore, not be used without being prepared for the selected primary shaping process. Especially for high-end products, purification of metals, for example, is an important step before the primary shaping takes place. For ceramics (as shown in Chapter 3), the plasticity and green strength obtained with the mixture of the material should be adapted to be used in the shaping process and accordingly to the final product properties.

Shaping can take place by forming, e.g. casting and moulding, or subtraction by use of milling processes. But shaping can also be achieved by the addition of material in layers on top of each other, so-called additive manufacturing. Just a few technologies are used for silicate ceramics. Moulding and extrusion dominate the production process for brickwork.

The finer ceramics like stoneware and porcelain are within the same material category as earthenware, which is often used for bricks, while the finer materials are typically used for vases, cups, and art objects.

Besides the silicate-based ceramics, there is another wide variety of ceramics referred to as technical ceramics. These technical ceramics are used for a broad range of products. Examples are ceramic disk brakes for sports cars, gas burner nozzles, medical implants, and even nuclear fuel (Kollenberg, 2009, p. 540, Reeve, 1975, p. 59). Technical ceramics are processed with different processes, amongst which moulding, casting, sintering, and hot pressing. Technical ceramics are produced by extrusion, too, but this method differs from the method for silicate-based ceramics. While fine ceramics are purer than silicate-based ceramics, most of these technical ceramics are processed in the form of a powder.

Figure 2.7 Aït-Ben-Haddou Kasba
Morocco - The city was founded in +/- 750 BCE. The type of bricks used match the market needs. Although it is assumed that all buildings in the city date from after 1700, the brick types used are not different form the traditional building products.

Figure 3.1 Plaza de España Aníbal González - Seville, Spain

3 State of the art

Brickwork has evolved, especially over the last centuries. Processes were changed to improve the structural performance, but most improvements were driven by energetic performance, making it the main motive to change the bricks design and to rationalise the production processes.

This chapter lists these production processes and bricks as well as the influence of the geometry on the process. Since clay is a silicate ceramic material, the technical ceramics mentioned in Chapter 2 are not addressed beyond describing the evolution and state of the art of brickwork. The higher-grade silicate ceramics are addressed, even though they are partly processed with different production processes and result in products with different product characteristics, while being a material subcategory of silicate ceramics.

3.1 The application of brickwork

As mentioned, brickwork has evolved over centuries. This paragraph lists all notable changes and the relation between the products and production processes.

The bricks in brickwork are often attached to each other by a mortar, a glue-based material or by interlocking, if a dry stack system is used. The joints have a different thickness according to the space needed to align the bricks and due to desired aesthetics. Some dry stacked systems are mechanically interconnected with small steel anchors.

To reduce the thickness of the joint, bricks can be milled or ground after they are fired. Motivation to do so can be found in the accuracy needed for a dry assembling system, or to increase thermal performance by reducing thermal bridges, which especially occurs when thick mortar joints are used between perforated insulating bricks, and in the aesthetics of the masonry.

Modern brickwork can be divided into different categories. A general distinction can be made between different appearances of the bricks, for example solid bricks versus perforated bricks. But a distinction can also be made in the way the bricks are used as either structural load-bearing components or as non-load-bearing brickwork for cladding, for example. The higher the temperature at which bricks are fired, the harder the material and the more resistant to weather influences it becomes, but its insulating performance often decreases. The separation in material quality influences the application of the final product. Table 3.1 shows the main structural and cladding applications of clay products in the built environment.

D. de Witte, *Clay Printing*, Mechanik, Werkstoffe und Konstruktion im Bauwesen 62, https://doi.org/10.1007/978-3-658-37161-6_3

Figure 3.2 Hospital de Sant Pau
Lluís Domènech i Montaner - Barcelona, Spain

Table 3.1 Main structural and cladding applications of clay products in the built environment

load-bearing protected	**load-bearing not protected**	**non-load-bearing protected**	**non-load-bearing not protected**
vertically perforated hollow clay bricks	load-bearing masonry	infill perforated masonry in concrete structures	brickwork rain shields
insulated vertically per-forated hollow bricks	lintels	ornaments	lintels
lintels	corner bricks		corner bricks
	key stones in e.g. arches		key stones in e.g. arches
			ornaments
			roof tiles

3.2 History and evolution of brickwork production

Brickwork is made from silicate ceramics. Shaping bricks by use of moulds dates back millennia. Today's processing technologies have been refined and influenced by performance improvement, cost effectiveness, and regulations; but they are still based on the first principles of brickmaking.

The oldest brickwork that has been discovered dates back to 14,000 BCE in Egypt. The first traces of fired bricks date back to 5,000 BCE. The history of our modern brickwork starts with the widely available material clay. All over the world dwellings are built with clay. The application differs but the principle of mixing silicates and aggregates remained the same over time. The coarser particles of sand are mixed with the fine platelets of rock, known as feldspar. When the mixture dries, the coarser particles like sand and chamotte prevent the material from shrinking. Straw and other fibres were and are still used as reinforcement to increase the tensile strength.

At the time when fired bricks were used, natural stone was used, too. When around 2,500 BCE, harder and better tools could be made due to the discovery of bronze, the accuracy of the natural stone bricks dimensions improved and they could be used as ashlar. At that time, fired bricks had improved over the centuries, as well (Pfeifer, G., Ramcke, R., Achtziger, J., & Zilch, K. 2001, p. 10). The Romans used brickwork and concrete as construction material. Many of the bricks where clad with natural stone on the outside. The desire to build higher and bigger buildings increased the desire for materials with better properties.

After some time of absence, fired bricks were reintroduced in the north of Europe, while the knowledge of the production process was maintained in the southern European countries during this era. The firing process of clay could be better controlled again, and the structural integrity of this building material increased, as higher buildings and especially churches, like the Basilica of Constantine in Trier, Germany (310 AD), exemplify. Although early examples can be found in northern European countries, nowadays considered as brickwork countries, the first places where bricks were used after their reintroduction can be found in the south of Europe (Stenvert., R. 2012, p. 17). Figure 3.3 shows a timeline and historical background of brickwork.

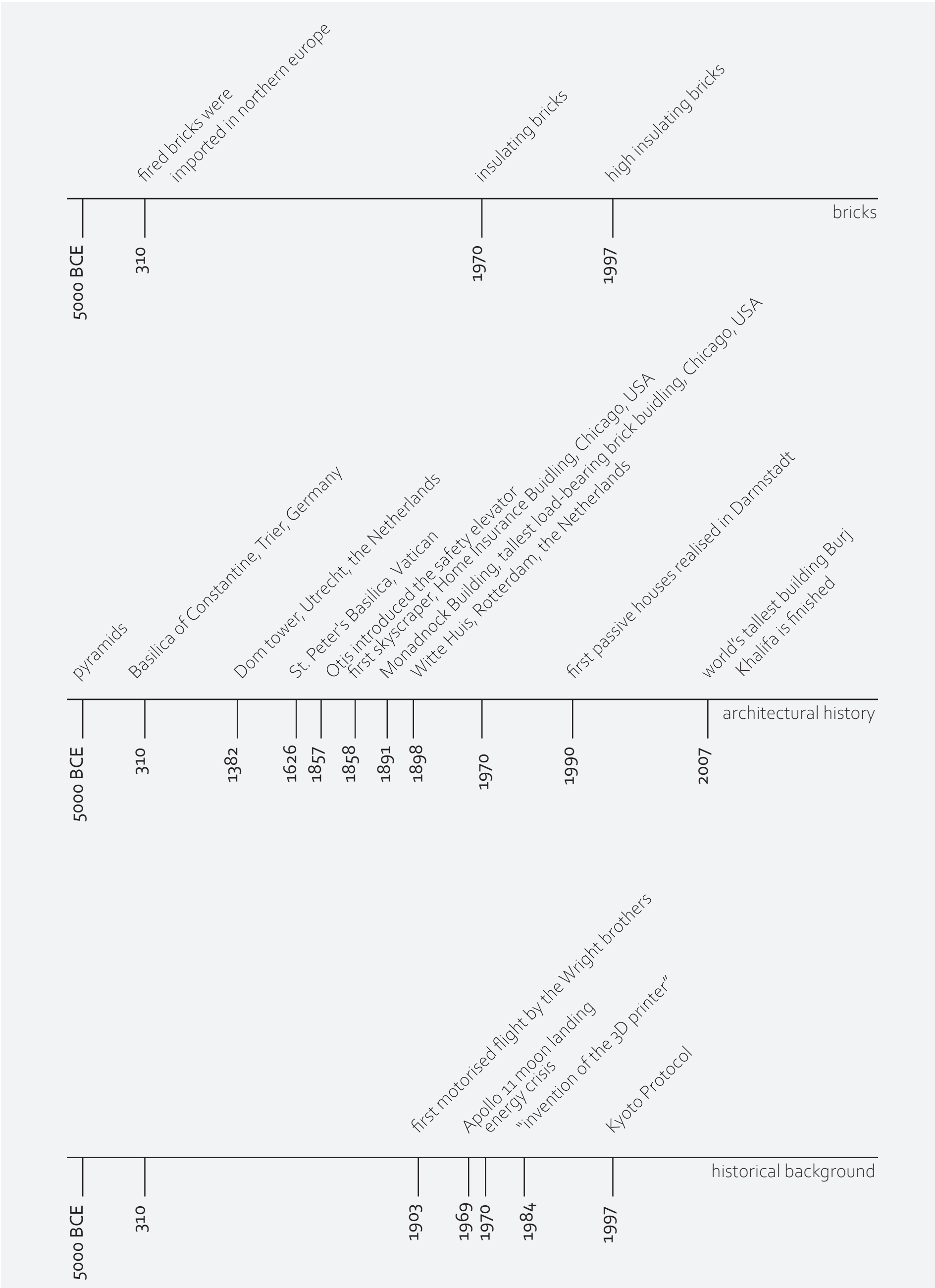

Figure 3.3 Timeline
Brickwork has been used all over the world, in different periods, building types, and constructions.

Figure 3.4 Aït-Ben-Haddou Kasba
Morocco - The city was founded in +/- 750 BCE. It is assumed that, today, all buildings in the city date from after 1700, but are highly related to the traditional buildings from before that time.

3.3 State of the art brickwork

Bricks as a construction material have shown their durability. Due to the awareness of energy consumption and building-code regulations over the last decades, brickwork itself, but also the production technologies became more advanced, not least to improve production efficiency. Clay can be processed with different production technologies. The external influences triggered the technical performance of both, the production process as well as the brick itself. These influences can be categorised as follows:

(1) Product performance driven. The desire of mankind for higher, bigger, better building construction, for which better products were desired.
(2) Production technology driven. The invention of new production technologies and especially sensors that allowed for different and/or better products.
(3) Economically driven. Influences that triggered efficiency of the product and/or production technology. An example is the need for better insulated houses during the energy crisis. This crisis led to the vertical perforated hollow clay blocks with insulating material infill as still known and widely used nowadays.

After centuries of building with clay materials, based on tradition either fired or dried, the products changed in appearance and, especially over the last decades and encouraged by the industrial revolutions, bricks became more standardised and functions were

Figure 3.5 Monadnock Building
Tallest load-bearing brickwork structure. Chicago, USA - Image by U. Knaack

embedded. Noticeable is the integration of insulation in load-bearing bricks next to new construction systems that increase the thermal insulation as a reaction to the global energy crisis so that buildings would exhibit lower energy consumption during the user phase. The rationalisation of the built environment with the application of (reinforced) concrete, steel, and glass after the industrial revolution made it possible to use masonry in a material-respectful way (Pfeiffer, G. et al., 2001, p. 6.). Due to the wide variety of bricks available, modern brickwork can almost always provide a suitable solution in the built environment.

Just like the production technologies and the different bricks, the clay firing process can be divided into different groups. Structural and protected brickwork is made of clay fired at a lower temperature. Weatherproof bricks are fired at higher temperatures which causes vitrification of the clay. So-called earthenware or terra cotta is used for ceramics fired at lower temperatures. The more resistant bricks are made from material with a slightly different composition and are fired in the higher temperature regions up to 1100-1300 degrees, where vitrification can take place.

The brick changed over the years. A general improvement is the dimensional accuracy and the variety of colours in which clinkers are made. Also, dry stacking systems emerged. The bricks of these systems can be used for brickwork without using a binder between the individual bricks. However, from a distance the bricks still look like traditional masonry. Besides clinker bricks that are often used as a cladding material, large, more structural clay building blocks like the vertical perforated hollow clay blocks improved over the last decades. The performance of these bricks regarding insulation and load-bearing capacities has increased. Free-form bricks are not yet made in fully automated industrial processes.

Higher grade ceramics known as stoneware, porcelain, and bone china have different material compositions and can be fired at higher temperatures, too. Due to the difference in material composition and material behaviour, e.g. shrinkage and memory of form in the case of porcelain and bone china, different production processes are applied. This chapter describes the evolution and the motives in more detail together with the processes used for higher grade ceramics. The next paragraphs describe the modern production technologies in context with the products they produce.

3.4 Production processes

Most commonly used processes to form a product are casting, extrusion, forming, machining, moulding, and joining. Nowadays, production technologies for silicate ceramics for bricks are primarily based on two principles; the extrusion processes and moulding processes. These technologies can be used with raw materials, but combinations are possible as well. Steps after the first production process are referred to as post-processing. With post-processing, e.g. imaging and coating, the appearance of clay products can be changed. These processes affect the surface of the part. The main difference as a result of the production process are the aesthetics of the brick, on the one hand, which is a direct result of the process and the load-bearing and insulating performance, on the other hand, which are also influenced by the production technology and material used. Besides the production technology and the type of ceramic used, other parameters in the production processes can be changed to obtain different product characteristics. Examples are:

(1) Firing temperature
(2) Adding additives to change the porosity, for example

Adjustments can be used to change and optimise:

(1) Product characteristics e.g. strength, thermal resistance, and water tightness
(2) Emissions during production
(3) Energy consumption of the buildings in the user phase
(4) Overall production costs

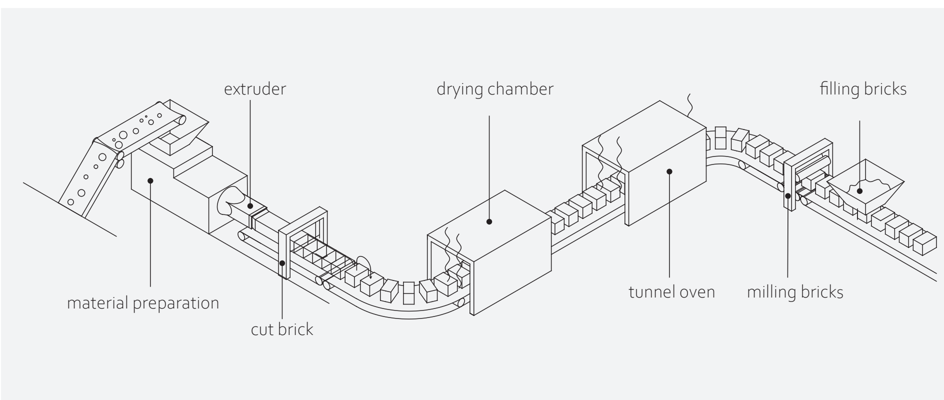

Figure 3.6 Modern extrusion process

Table 3.2 Ceramic types and common characteristics

material	terra cotta	stoneware	porcelain
firing temperature [°C]	around 1000	1100-1300	1200-1400
production technology	- extrusion - moulding - hand forming	- extrusion - moulding - hand forming - casting	- extrusion - moulding - hand forming - casting

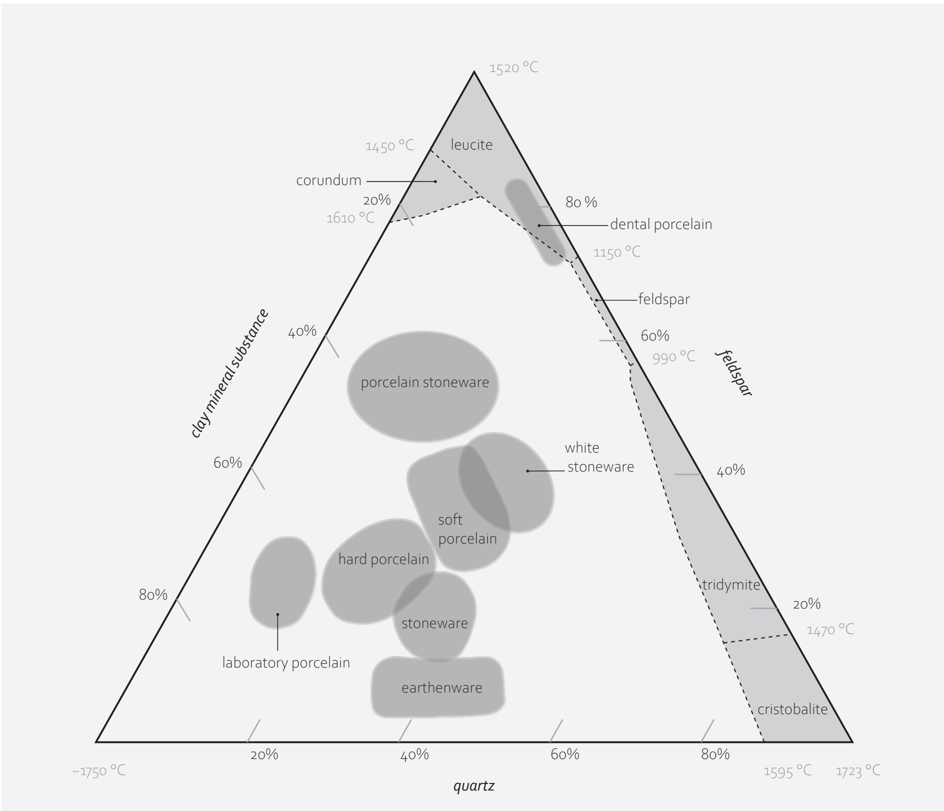

Figure 3.7 Silicate ceramic groups
The vitreous phase of porcelain stoneware: Composition, evolution during sintering and physical properties. Based on C. Zanelli, M. Raimondo, G. Guarini, M. Dondi, 2011, p. 3253 and Pampuch, R., 2014, p 24.

However, as mentioned above, many processes are based on the two main production principles extrusion and moulding, while for higher grade silicate ceramics they are also based on casting processes. Other techniques exist as well, for example mixing a glaze with the clay mixture. One such product is known as Egyptian paste, which changes the appearance of the ceramic.

Different materials are combined to make terra cotta, stoneware or porcelain. Table 3.2 shows common material mixtures and processes used. Since there are many different mixtures, this is just an indication of the material compositions. Figure 3.7 shows a bandwidth of the materials and their composition. However, the material for a specific product can differ and the purity and availability of the classic ceramic clays differ depending on the location where they are mined.

Due to the fluctuations in the material composition, the traditional production processes have to be adapted to cope with these flaws. They will have to function within a bandwidth of materials and their characteristics. The material quality, the purity, and replicability of the material mixtures increased over the years. The material is often chemically analysed before a new batch of material is used. So-called differential thermal analysis (DTA) is employed to analyse the endothermic and exothermic reaction of the material during firing. This provides information about the amount of organic material and chemical-bound water. A mineralogical analysis is carried out to look at the material's composition to predict its behaviour during shaping and firing. In comparison to technical ceramics, silicate ceramics are a mixture of natural materials with changing properties. Silicate ceramics are therefore less pure than technical ceramics. This means that, although materials are chemically analysed, it is important that the production process is able to cope with these fluctuations as shown. The main properties, which are characteristic for clay and can be changed and controlled by their mixture, are:

(1) The plasticity
(2) The strength of the greenware (unfired clay bodies), also referred to as green strength of clay bodies
(3) Shrinkage and warping
(4) Porosity
(5) Texture
(6) Glaze response
(7) Thermal resistance
(8) Colour (by adding pigments)

3.5 Extrusion processes

Extrusion is a continuous or batch process that pushes the clay through a die. The extruded profile is then cut into products that have the desired length. Although this process

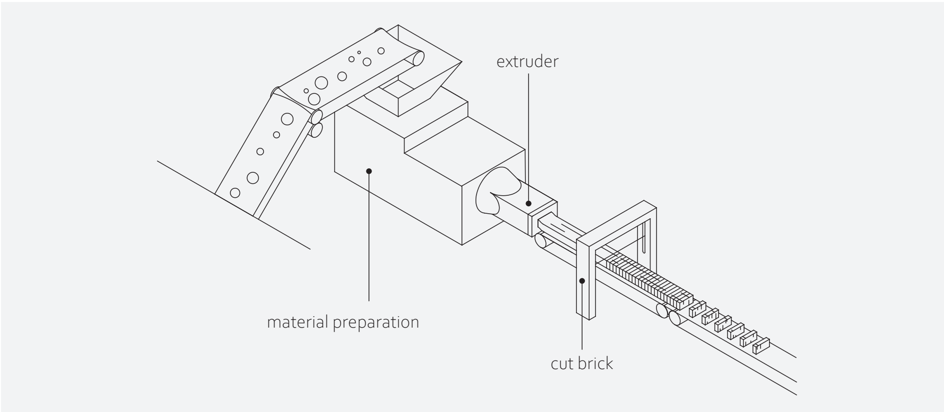

Figure 3.8 Rectangular extrusion
Schematic extrusion process. On the left, the mixed materials are fed into the extrusion mechanism. They are compacted and evacuated, then extruded. After extrusion, the bricks are cut and transported to the drying chamber (not shown).

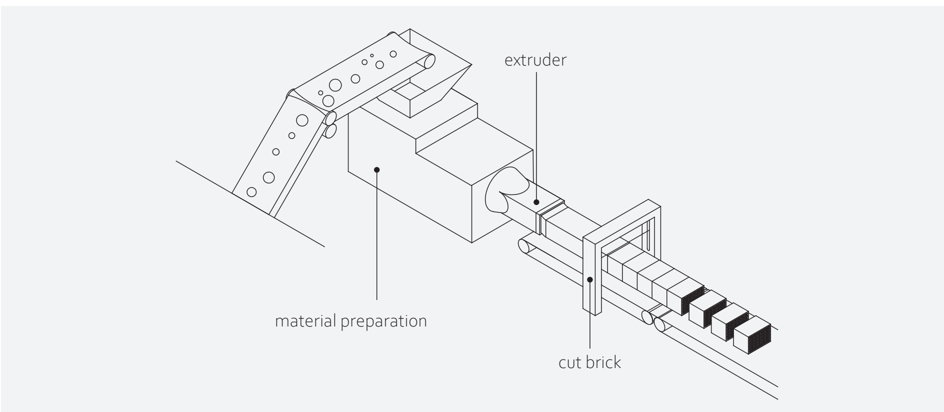

Figure 3.9 Honeycomb extrusion

seems simple, the material and process needs to be controlled well to obtain a good quality brick. The form of the brick is not limited to a rectangular shape.

3.5.1 Rectangular extrusion

The material is mixed before it enters the extruder. In the extruder, the material is compacted and evacuated before extrusion. Simple linear extrusion can be used to extrude clinker bricks, for example. Figure 3.8 is an abstract representation of rectangular extrusion.

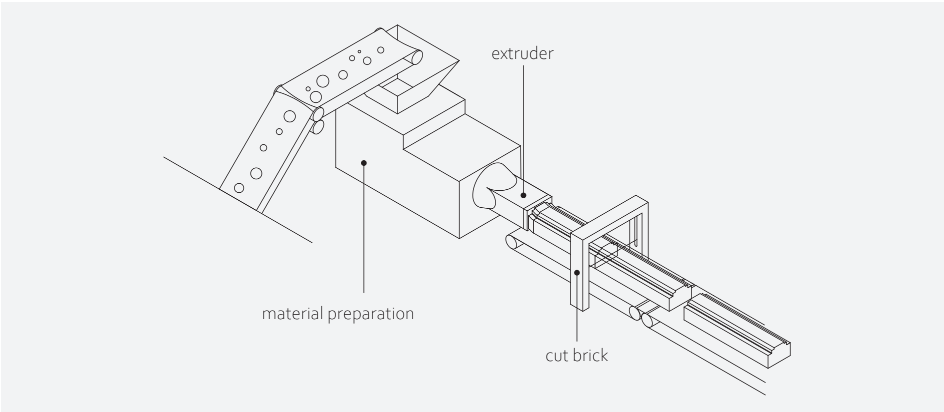

Figure 3.10 Extrusion of special geometries

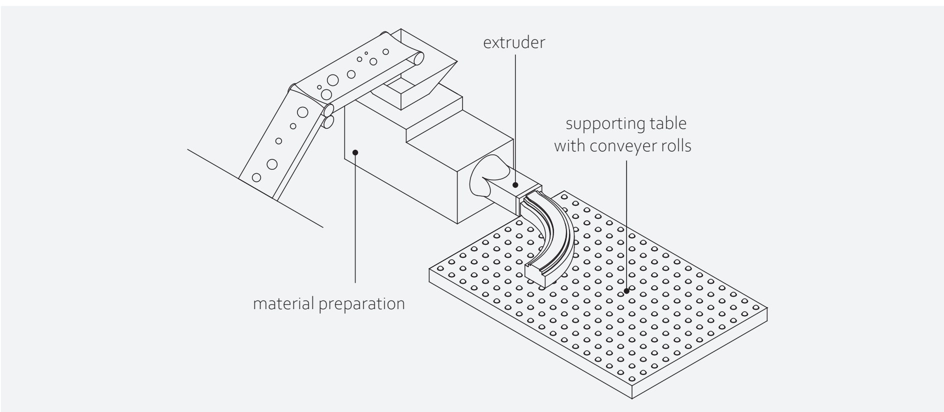

Figure 3.11 Extrusion of curved geometries

3.5.2 Honeycomb extrusion

Honeycomb extrusion is a continuous process that pushes the clay through a die. The extruded profile is then cut into the desired length. The difference to normal extrusion lies in the die used for this process. Normal extrusion uses a simple opening, e.g. a rectangle, through which the material is pushed. The die of the honeycomb extrusion has an additional geometry inside the main opening to make internal openings along the direction of extrusion. Small metal guides are installed on the inside of the die. These guides function as brakes to regulate the flow and the extrusion speed (Händle, F., 2007, p. 230). It is important that all parts of the sections are extruded with the same speed to avoid warping

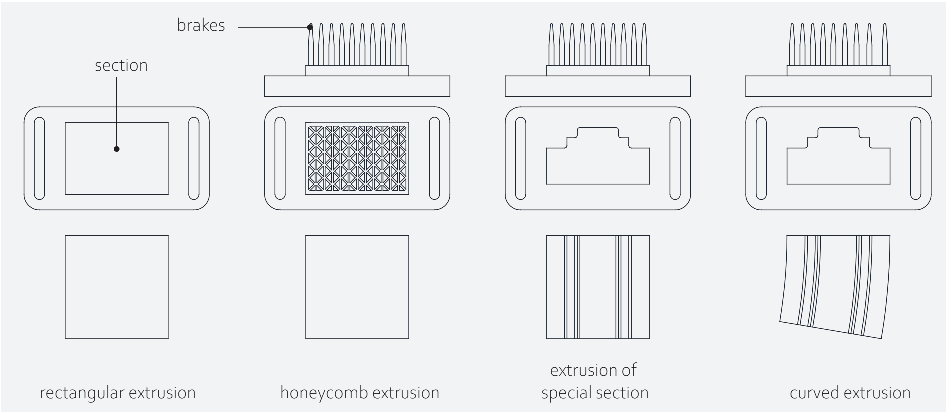

Figure 3.12 Different types of dies used in a brick extrusion process

and obtain a straight extrusion profile. The resistance should be equal across the complete cross section of the die (Händle, F.,2007, pp. 228-229). A difference in resistance and local extrusion speed causes the geometry to warp. However, by controlling and adjusting the internal speed of the material in the die, curved extrusions for curved lintels, for example, can be made (Figure 3.11).

3.5.3 Extrusion of special forms

Special geometries with less symmetric profiles can be extruded by use of a special die. These dies not only have a more sophisticated cross-section, but also additional guides to control the speed (Figure 3.12).

3.5.4 Direct post-processing of extruded bricks

To adjust the geometry, the surface can be embossed directly after extrusion. Patterned rotating drums used to emboss the outside of the bricks roll over the freshly extruded clay (Figure 3.13), a process also referred to as rouletting (Hoosen, D. & Quinn, A., 2012). Other mechanical tooling to create (random) surface patterns, e.g. metal rakes, are used for grooves and raked surfaces (Mulder, K., 2016, p. 139). After the material is extruded it is pushed onto a conveyor belt. A speed-synchronised gantry moves across this belt to cut the bricks in straight lines with a wire. After cutting, the gantry moves backwards, synchronises its position and speed before it cuts the next brick. Corners can also be cut off to change the brick's appearance (Figure 3.14). Many post-processing methods to adjust the brick's surface are individualised by brick manufacturers to obtain a characteristic and distinctive surface texture. Due to the company specific application, these embossing and

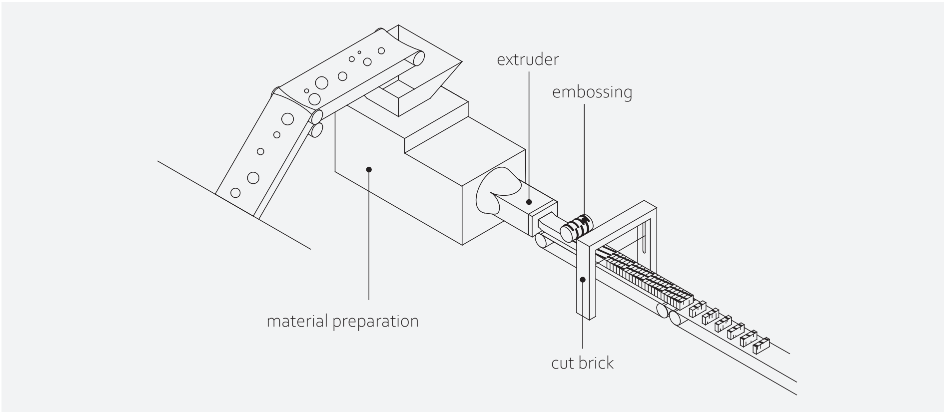

Figure 3.13 Post-processing
A pattern is embossed in the extruded bricks.

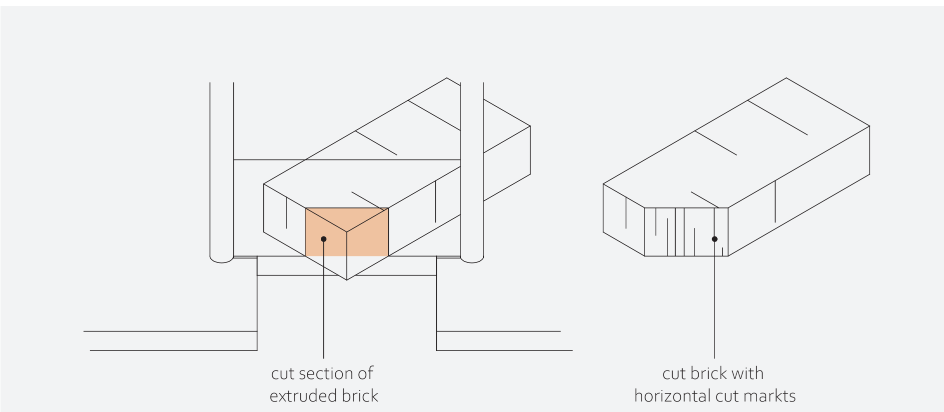

Figure 3.14 Cut extruded brick

raking techniques are not well described in literature (Mulder, K., 2021).

After drying, the bricks are fired, post-processed when needed, checked during quality control, and packaged. Depending on the products, the drying and firing conditions change with the material used.

3.5.5 Additional processes after extrusion

After producing the desired shape of the brick, the bricks can be glazed. Often, glazed bricks have to be fired a second time.

Filigree structures are more difficult to make with automated extrusion and hand

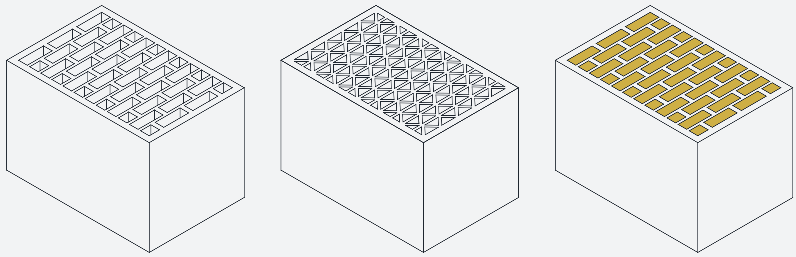

Figure 3.15 Evolution of vertical perforated building blocks

forming technologies. For perforated bricks, the focus on energy efficiency in the user phase of the buildings led to perforated bricks with many small vertical chambers. After a few years, even stricter regulations regarding energy efficiency forced the brick industry to think about other solutions. The result are bricks with insulation material inside the chambers. The traditional extrusion process did not require the very filigree structure of the perforated bricks to prevent convection, because of the insulation in the vertical shafts. The wall thickness between the perforations increased and led to a more stable brick which could be extruded more easily. However, less filigree bricks have to have the same or even better insulation performances; these bricks need to be post-processed after firing. They are ground to increase the dimensional accuracy like the predecessor with the filigree walls, where after they are filled with a mineral wool or wood fibres. Filling the bricks with those fibres is performed on a vibrating table. The brittle bricks need to withstand these vibrations; the increased wall thickness helps.

Another advantage of the insulation inside the bricks is the fire resistance of the wall structure. In contrast to insulating materials on the outside of the vertical perforated clay blocks, insulation on the inside will not spread fire along the wall as easily as outside insulation. This is becoming important since vertical perforated clay blocks are used for higher buildings nowadays, where fire safety and regulation play a critical role.

3.6 Moulding

The simplest production technology to produce bricks is moulding. The process dates back to 5000-4500 BCE, when both dried only as well as fired bricks were used by the Babylonians (Stenvert, R., 2012). The control of firing bricks over the millennia led to the craftsmanship of the glazed bricks in the Ishtar Gate of Babylon, which dates back to

575 BCE. The technologies of the high tide of craftsmanship regarding the production of bricks was first rediscovered by the Romans. From then on, the production was redeveloped and advanced.

There are several moulding processes to produce bricks. They can be divided in continuous and batch processes. The continuous processes are the punched brick production technology (German: Wasserstrich) and automated hand formed brick production technology.

3.6.1 Punched brick production technology

Punched brick production is a production technology where material is moulded in a rotating disc on a table. The table's disc contains openings that form the wall of the moulds. This rotating disc slides over a plate, which forms the bottom of the mould during filling and when the press starts to apply force from the top on the material-filled mould. In the first phase of the demoulding process, a geometry integrated into the press mechanism can emboss the clay. When the opening in the rotating disc is no longer above the plate, the bottom of the mould is open and the press pushes the brick gently out of the mould onto a conveyor belt. The opening turns to a different side of the machine where it is cleaned with water and can be refilled, where after the process is repeated. The openings are filled through a nozzle. The size of the nozzle matches the size of the opening. (Mulder, K., 2016, p. 139)

With this process the brick's form is determined by the 2D geometry of the opening in the disc and the imprint on the press. The material processed is highly viscous, because otherwise the bricks would not have enough green strength to be pressed out of the temporary mould. A typical characteristic of this production process are the vertical lines on the brick that result from the demoulding.

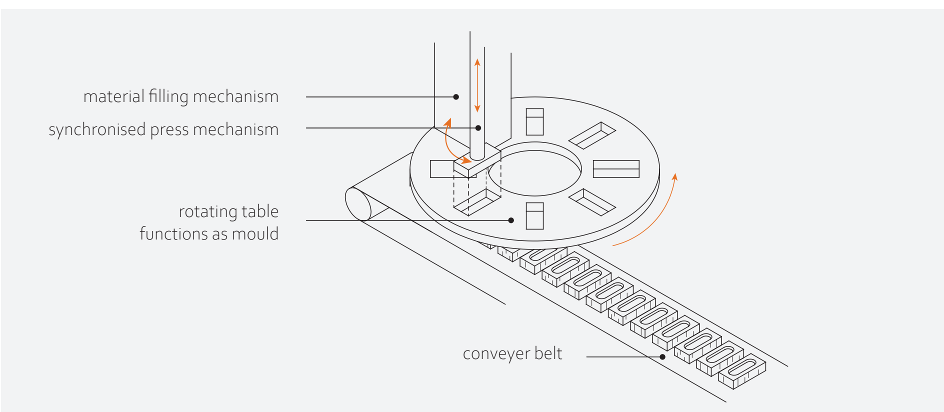

Figure 3.16 Punched brick production

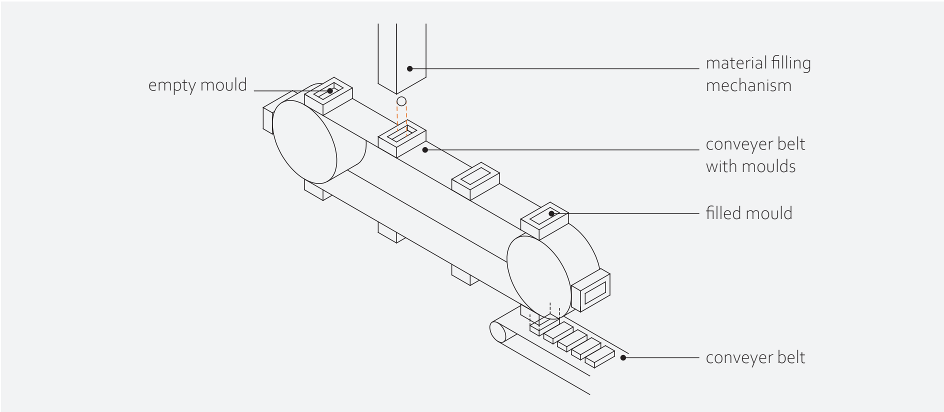

Figure 3.17 Mechanical hand formed brick

3.6.2 Mechanical hand-formed bricks

This process uses a conveyor belt that transports the moulds. The mould is filled from the top with a, sometimes sand-covered, piece of clay that falls into it. The characteristic surface is caused by the deformation of the clay piece when it is thrown in the mould. These bricks were used to be made by hand but the process has been automated. Nowadays, an automated process can generate bricks that look like handmade bricks (Mulder, K., 2016, p. 139). This process requires a high viscous material, but little force is applied to the material that is put in the mould. This combination of high viscous material and the lower applied force on the material increases the amount of surface irregularities in comparison to the moulded brick (Figure 3.17).

3.6.3 Moulded brick

Moulded bricks are made by use of formwork where a controlled amount of material fills the openings in the mould (Figure 3.18). Before it is filled, the mould is often covered with sand. After filling, extrusion is used to push the material into the mould, which accommodates multiple bricks (Mulder, K., 2016, p. 139; van Hunen, M., 2012, p. 31). The material surplus is removed and can be reused. When the formwork is filled, it is turned upside down and the bricks fall onto a conveyor belt. The sand makes demoulding easier. Finally, the bricks are put in a drying chamber.

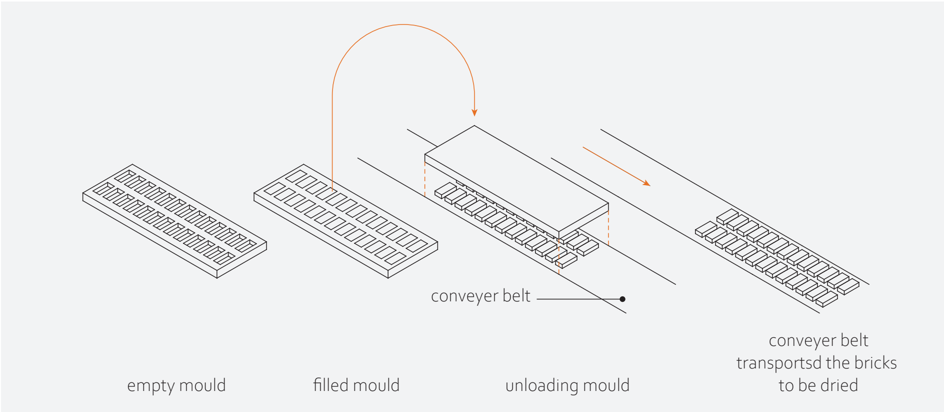

Figure 3.18 Moulded brick

3.6.4 Further adaptation of the geometry of moulded bricks

The form of extruded bricks can be changed by changing the die of the machine, but the form of the bricks made with formwork can be changed, as well. Inserts inside the moulds for moulded bricks can be used to create different forms (Figure 3.19).

The openings and the contra-form on the press mechanism of the punched bricks could theoretically be changed to change the brick geometry. The brick can also be modified by changing both the dimensions and the design of the openings and surface of the stamp. If only the geometry of the stamp within the press mechanism is changed, only the top surface can be modified.

For individual bricks, special formwork as discussed above or additional production steps in the forming process are needed. Those additional steps can be additional cuts on an extruded brick, but also the complete reshaping of a brick by hand in the aforementioned “hand-forming mould”. This fabrication method is time intensive and is significantly more expensive than high volume automated processes. Cutting parts off of bricks produced with moulds will change the surface texture (Figure 3.20). If no pattern is embossed or the surface is not raked, extruded bricks are very smooth. The faces of the cuts will therefore be similar to the other faces of these bricks. It is a challenge to mimic the surface of a hand-formed brick.

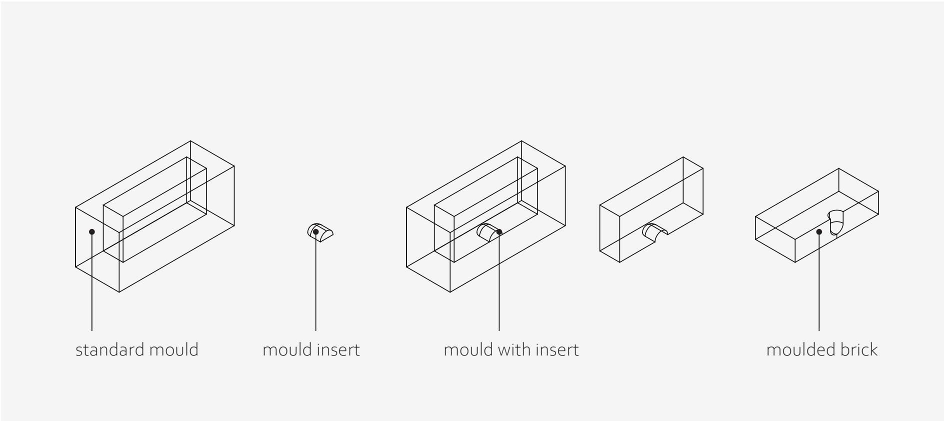

Figure 3.19 Mould with inserts to adapt geometry

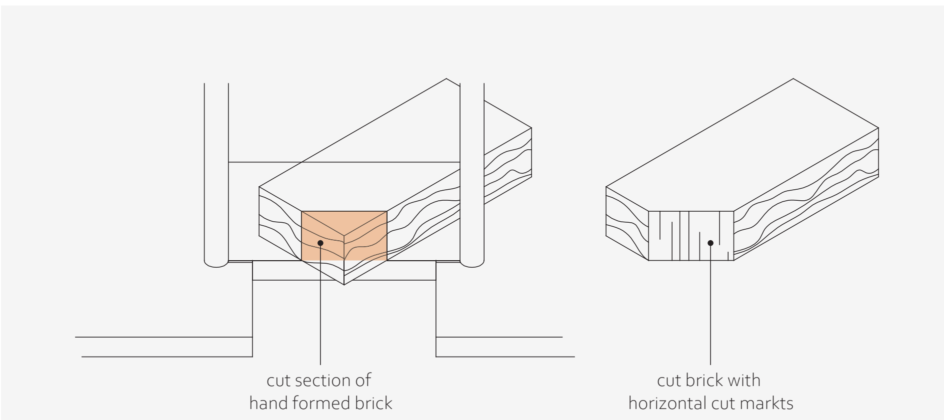

Figure 3.20 Cut hand-formed brick

3.7 Post-processing bricks

When the products are bisque fired, they are stable enough to be post-processed. Some post-processing steps can be carried out if the dried-only green body is strong enough. Examples of post-processing are milling, glazing or decorating before or after glazing with different techniques. There is a clear distinction between the post-processing of load-bearing and insulating bricks and the post-processing of bricks used on the outside of the buildings.

Figure 3.21 Glazed bricks
Witte Huis, Rotterdam, the Netherlands

Figure 3.22 Free form masonry
Wall Relief no. 1, Weena, Rotterdam, the Netherlands

3.8 Production processes for fine silicate ceramics

The production processes for finer silicate ceramics differ from those utilised for earthenware. The technology used on the product and the processes require materials with different characteristics. The main processes used for fine silicate ceramics are hand forming, casting, slib casting and extrusion.

3.8.1 Hand forming

Many clay objects are formed by hand. This is the oldest way to shape the products. Nowadays, potters still form vases, for example, by hand using a rotating table. Ornaments that do not share the rotation axis of the vase's core are manually attached later.

3.8.2 Casting

Casting is often used for relatively thin clay products that have a detailed surface. A liquid ceramic is poured in a mould. Due to the higher amount of water, the product will shrink more than products made with a clay with a lower water ratio. To reduce the shrinkage, additives and chamotte are used.

3.8.3 Slib casting

Slib casting is often used to make filigree, thin, hollow (porcelain) products. The mould is filled, and the drying process of the liquid ceramic starts immediately in the mould, where the ceramic hardens on the mould's surface. Often, the mould is slightly higher than the desired product and is filled with material above the edge of the desired models shape to compensate for the shrinkage of the material during drying. After a certain amount of time, the liquid material on the inside is removed and the model is demoulded, where after the ceramic layer on the inside of the mould is dried. Any additional material is removed before firing. The mould must be able to cope with the internal stress caused by the shrinkage of the material, which requires it to have a certain flexibility.

3.8.4 Extrusion

Extrusion is applied for finer silicate ceramics, too, but the process often involves batches of material in pre-filled containers instead of the continuous mixing and feeding systems used in brick factories. Therefore, the extrusion pressure can be higher. A generally higher viscosity due to a higher amount of non-reacting chamotte could reduce shrinkage.

Figure 3.23 Fine ceramic wall decoration
Sultan Qaboos Grand Mosque, Musqat, Oman

3.9 Firing fine ceramics

Firing fine ceramics does not differ from the firing process for brick products. However, porcelain is often fired with so-called setters to guarantee the final shape. In the clay industry, porcelain is known for its memory. This memory causes porcelain to want to transform back to its original shape if it is abruptly bent during the shaping process; a factor that can cause large deformations during firing. Even if the porcelain is carefully shaped, setters are recommended during firing.

Figure 4.1 Brickwork façades and modern curtain walls in the background
49 Bull’s Head Passage, London, United Kingdom

4 Research framework

The scope of this research is the application of AM for building parts. The application can be structural, but also for aesthetic, free-form purposes. Depending on the material and technology used, different qualities can be produced. In this research, the main AM technologies will be discussed and compared. Silicate ceramics (clays) are the most commonly used ceramic materials in the built environment. To limit the scope of this research, clay-based silicate ceramics have been selected as the material category that will be addressed in this research. This decision is based on the material's extensive usage and its role as construction material in the built environment.

4.1 Motivation

Brickwork and clay products have been used for centuries in our buildings. The production processes changed over the years to produce better products, but also to optimise the efficiency of the production process. Due to the high efficiency of some of those processes, some products made by use of more labour-intensive processes became relatively expensive compared to those products that are highly standardised and produced in an automated process. Due to the lower prices for the bricks, bricklaying itself tends to have a bigger share in the overall costs. Advanced patterns as seen in e.g. the Amsterdamse School, an architectural movement in the beginning of the 20th century, are not common anymore. Brickwork became less versatile due to automation and many contractors tend to reduce the share of the labour costs for brickwork.

The motivation of this research is to investigate how new production technologies can help in the development of brickwork and if they can provide for a solution to keep this characteristic building material attractive and unique. The rationalisation of the building industry did not only come with improvements. Concessions were made on the level of detail and individuality of the façades. This architectural style (i.e. modernism) came with buildings that missed a relation to the human scale according to Jah Gehl (Rodrigo, A., 2017). Compare the brickwork façades to the high-rise buildings in the city centre of London (Figure 4.1). By adding more individualised designs to the buildings, the detail and scale can be brought back. Over decades, the newer production processes led to less differentiation within the product range, but the fourth industrial revolution might change this.

An indisputable step is to look at other industries within the fourth industrial revolution, at how new technologies have been implemented and if they could be implemented

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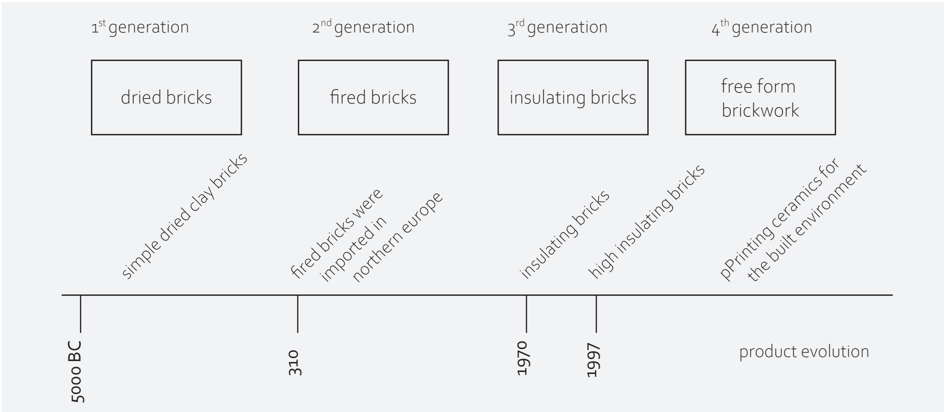

Figure 4.2 Product process development

in the building industry. In the case of the building industry, almost every building is different, or the buildings are made in small series. Individual formwork is expensive and therefore not always feasible. Furthermore, not all forms can be fabricated using traditional forming processes for bricks (described in Chapter 3). New processes, e.g. AM, are utilised in other industries with different materials; and individualised building components and solutions are becoming more common in the built environment, as well.

The fact that the costs per product in other industries do not change significantly and that it is possible to produce free-from products with new functions with standard materials, is a motivation to investigate if this is possible, too, for silicate ceramic (clay) building products. The pursuit to make the human dimensions visible again, to initiate the reaction between the building and the user at a different level, to investigate the possibilities of AM for the built environment, and especially the interest in AM for classic ceramics are the main drivers to investigate the AM production processes, how they can be utilised for ceramic building components in a beneficial way, and which products can be made by use of this relatively new technology.

4.2 Research questions

Research questions have been formulated to investigate AM when utilised to produce silicate ceramic (clay) building parts. When this research was initiated there was no research on clay-based, additively manufactured structural building parts carried out yet. For a complete understanding of AM, the production technologies, the products and material, along with the history of brickwork, process technologies and the future potential need to be investigated. The research questions cover a wider variety of subjects directly related to the AM process. The research is initiated to answer the main research question:

"How can structural silicate ceramic components be produced with an additive manufacturing process to increase the product's functionality, and to what extent can they be used in the built environment?"

Sub-questions related to the AM process are formulated to provide information on the history of AM for the built environment, background information on production technologies used to fabricate silicate ceramics, information regarding the AM processes, the materials, the products and the performance, and to enumerate possible future development.

Chapter 1

- For what purpose is AM used in the built environment?
  - Which materials are used?
  - Are these products prefabricated?
  - To what extent, regarding functions, are these products embedded?

Chapter 2

- How can clay as material be categorised, and which of these ceramics are used in the built environment?

Chapter 3

- How are clay materials processed and which production technologies have been used?
- What is the state of the art brickwork?

Chapter 5

- How are the variety of AM processes categorised?
- How are the available AM technologies used to process clay?

Chapter 6

- What do clay products produced with AM look like?
- How do clay products benefit from AM?
- For which products can AM of clay be used best in the built environment, to benefit most of the possibilities AM offers?
- What are the determining and shared characteristics of designs for clay building products that benefit being produced with AM?

Chapter 7

- What are the process related conditions that need to be fulfilled by the AM technology to print silicate ceramic (clay) products that can benefit from an AM technology?
- What are the conditions derived form the clay building product designs that benefit from being produced with AM?
- Are there additional process requirements when an AM process for clay is applied on a larger scale?

Chapter 8

- What AM production processes can be used to process clay materials for the built environment?
- How do AM processes for clay function?
- Is post-processing needed after clay products are generated with AM?

Chapter 9

- Which clay material(s) can be used within the selected AM process?
- Which parameters influence a clay material mixture's characteristics in an AM process and how can they be adapted to optimise the material?

Chapter 10

- How is the selected AM principle best adapted for silicate ceramics?
- What does a production chain for AM of silicate ceramics look like?
- How can quality and replicability be achieved?

Chapter 11

- What is the aesthetic performance of the additively manufactured clay building components by use of robocasting?
- Which structural compression and tensile properties do the printed clay products have?

Chapter 13

- What are the potentials of AM when utilised for clay products for the built environment?

Chapter 15

- How can AM of clay evolve?

4.3 Methodology

To investigate AM for processing clay materials to produce products for the built environment, the methodology in this research is formulated to provide insight in available processes and the challenges of processing clay.
Figure 4.3 shows a flowchart with the subjects of the research methodology used. The subjects mentioned will be replaced by specific topics which are related to AM of clay for the built environment.

To design a production process that can produce products which benefit from a specific production technology, the methodology focusses on the relation of the design of products and the design of a production process. Studies define concepts and needs, which will be developed into requirements and a final design (Larson, W.J., & Wertz, J.R., 1999, pp. 8-9). These studies involve a status quo to identify available technologies. When designing a production process and defining products that can be made with it, there is a direct relation between the production technology and design as indicated in the flowchart. However, other parameters are of influence, too. These parameters are the materialisation, technical characteristics of the product, the assembly of the products, and the utilisation itself (Eekhout, M., 1997, p. 128). A similar realisation of design and fabrication is described by M. Burns (1993, pp. 10-11). The subjects in the flowchart are investigated to answer the research questions and derive performance results as an input for improvement. The design is an evolving problem solving process (van Doorn, 2004, p. 29) which is cyclically repeated until design and assignment match (Kleijer, E., 2004, pp. 213-216). The final results will be translated into a “roadmap” to describe possibilities and future research topics.

To limit the scope of this thesis, the research is limited to silicate-based ceramics (clays) used in the built environment. This category of ceramics includes terra cotta and some fine ceramics and therefore includes the most broadly used type of ceramics in the built environment. The research questions were formulated during the preliminary research on AM of clay carried out at the Institute of Structural Mechanics and Design at TU Darmstadt. While experimenting with an extrusion-based 3D desktop printer, the first geometries showed the potential of the technology; however, it was not clear whether this would be the most adequate AM process category. To enumerate the parameters that influence the production process and characteristics of the produced parts, different material mixtures were processed with this machine.

To answer the research questions, the obtained knowledge and experience with the existing process is analysed, and the performance of the extrusion technology is compared

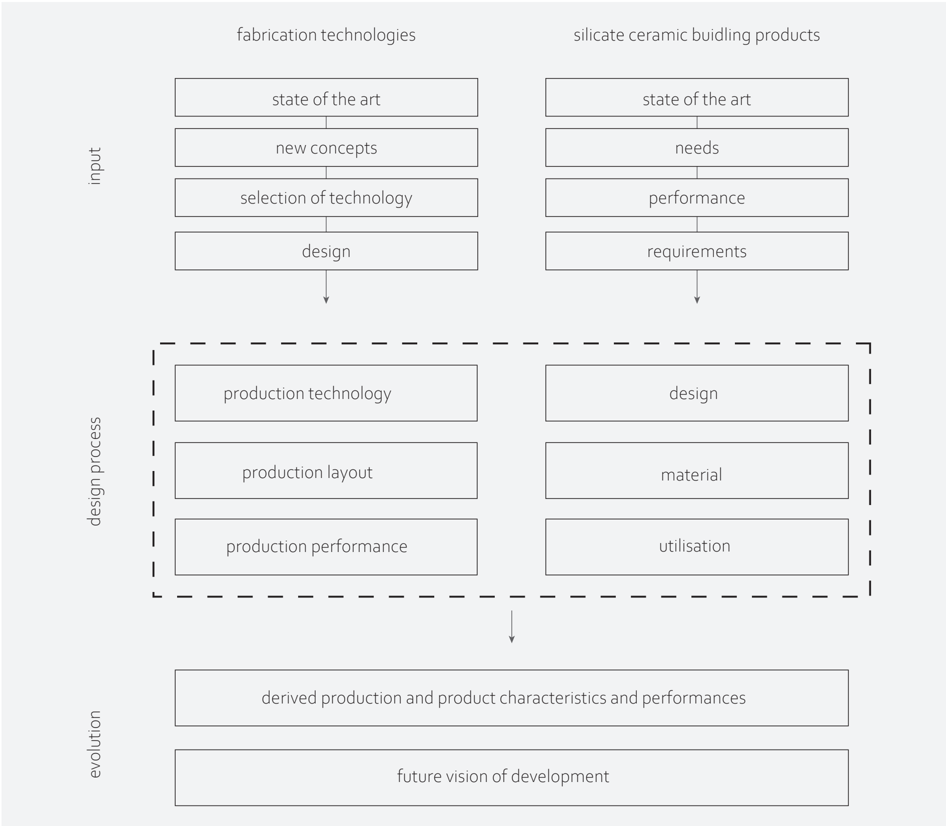

Figure 4.3 Methodology

to other AM technologies on the basis of process characteristics. The printed samples are compared and analysed, and the printer is reverse engineered to analyse how the available process works with silicate ceramics, and how it may be improved.

As mentioned before, a limited number of materials are part of this research to limit the scope of the thesis but some spread in the materials is necessary to simulate the fact that the composition of ceramic materials can change between material batches. Like in traditional clay production technologies the final process should be able to compensate for this, while maintaining accuracy and quality.

The research is divided into three parts, of which the first part provides background information. Describing AM for the built environment and a broader introduction to production technologies and the material. The second part of the thesis answers the main research questions related to the technology to process clay with AM. The objective is to describe the relationship between production technology, material, product, and product performance. The outcome of the analytical review of the different AM processes will form the base for a new adapted printer design. A design study is used to help define the conditions that have to be met by the new printer to print the desired products. After the technology is chosen and a printer has been designed and realised, the produced parts and process are assessed on aesthetic, load-bearing and building physical properties. The third part is an evaluation and future outlook. A future vision will reflect on the production technology and will show the possible application of it in the built environment.

Figure 5.1 Hospital de Sant Pau
Lluís Domènech i Montaner - Barcelona, Spain. The photo shows the combination of brickwork and highly decorative ceramic components. The Hospital de Sant Pau (Hospital de la Santa Creu i Sant Pau) was built in the beginning of the 20th century. The decoration is typical for the art nouveau style of that era.

5 Additive Manufacturing

AM is a production technology that stacks layers of material on top of each other with a layer thickness from 16 µm onwards (Tempelman, E., Shercliff, H., & van Eyben, B.N., 2014, pp. 188-189), making it a production technology that adds layers at a macromolecular level. This selective deposition of material can be realised with a variety of technologies.

As mentioned in the introduction, AM and the size of the components used in the process does not seem to be clearly defined. To frame this research and specify what the research questions apply to, the thesis explains what it defines as AM and the scale on which AM takes place. Since there is no general definition of AM and the related (raw) material particle size and production technologies yet, it can be assumed that everything that includes stacking is additively manufactured, only the scale differs.

Growth such as occurring in nature could be considered AM. Material is constantly added to obtain growth, even though it is more complex since material is also replaced – the healing of the product – which cannot be achieved without a complex network of "sensors" and mechanisms that deal with such inputs. But if AM is a production technology that extrudes material on top of each other, layer by layer, sliding formwork used for high-rise building construction should be considered an AM process with a low resolution, as many other extrusion technologies described before.

Using an STM microscope to positions atoms is not called AM while the process does indeed stack material on an atomic level. AM is described as a production process that builds products layer by layer, selectively adding materials on top of each other.

What defines AM and what is the difference with traditional production methods?

(1) Is it the behaviour of the layered product that is related to AM?
(2) Is it that there is no formwork used except for the printing bed and the nozzle?
(3) Is it that the technology is capable of generating shapes that cannot be made with regular production processes?
(4) Is it the stacking of 2D layers on top of each other forming a 3D object? Does this exclude using a robotic arm to produce a three-dimensional curve in the air?

Gebhardt et al. (2016, p. 2) define AM as a combination of two sub-processes which combine generating layers of material and joining these layers. A precise definition of what is and what is not AM is difficult to specify. "Additive manufacturing is the generic term for all manufacturing technologies that automatically produce parts by physically making and joining volume elements, commonly called voxels. The volume elements are

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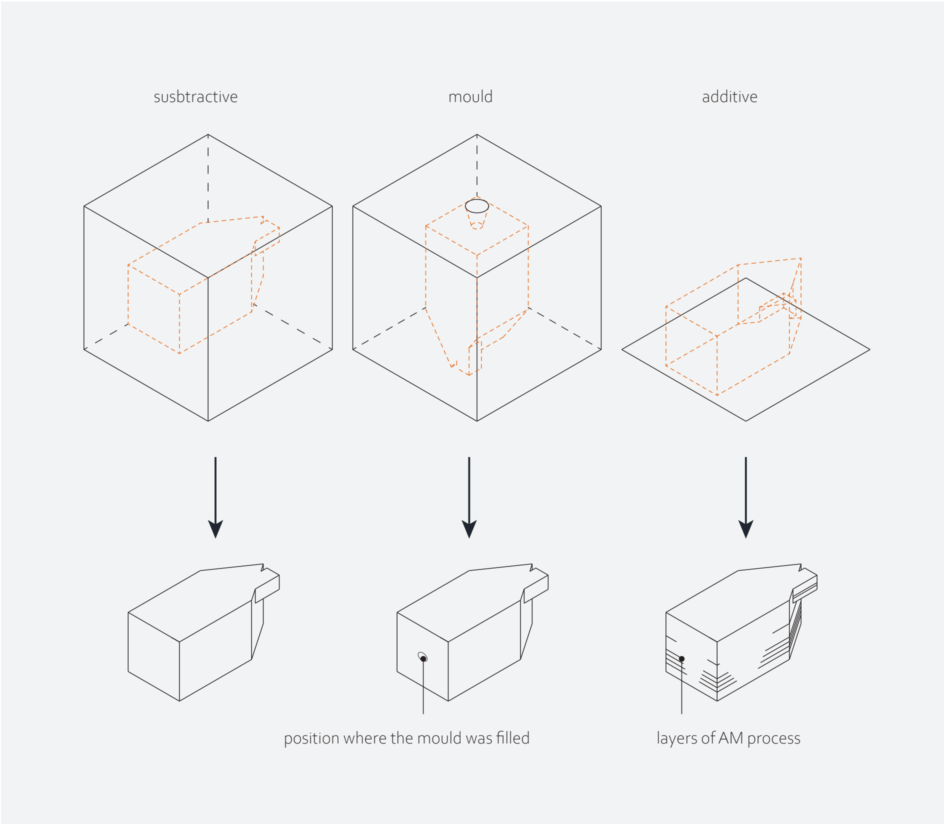

Figure 5.2 Subtractive manufacturing, moulding and additive manufacturing
Three main production processes show how a product can be made. With subtractive technologies, material is removed by milling, for example. Moulding uses a liquid material and formwork. AM uses just the raw material. AM reduces the amount of lost material.

generally layers of even thickness" (Gebhardt & Hötter, 2016). The standards DIN and ASTM only define the different production technologies in categories. But even without a precise, official definition, AM is becoming more accepted as a production technology. In aviation and the automotive industry, where optimisation in form and weight have a direct positive influence on the user phase energy consumption, AM is widely used to achieve this. In the built environment, weight and aerodynamics are of less influence on energy consumption, weight reduction may even have a negative influence, but free form, material reduction in general, and performance optimisation are driving forces to explore the possibilities of AM in the built environment.

Many production technologies are based on extracting material from a larger volume, by moulding whereby the material solidifies in its final shape, and additive processes, which also include extrusion processes as mentioned in Chapter 3 (Figure 5.2). Welding, or bolt-nut connections are often used to assemble and connect individual parts to form the final product. AM differs and is able to build a part by depositioning material layer by layer at the desired coordinates to form the final geometry. More complex geometries can be realised, it is independent of any formwork, small batch sizes are possible, and individual parts can be produced. Even the connection types can be adjusted and realised in one production process.

This chapter gives a brief introduction into AM for the built environment and compares the available technologies. The processes and technologies related to silicate ceramic (clay) are listed and discussed.

5.1 AM materials and processes

AM processes were first described in the late 1980s when the MIT and Chuck Holl worked on the first processes that, today, are categorised/indicated as AM. AM and 3D printing are both used to indicate the same process. Lately, the use of 3D printing is more common, however this name is used to indicate one specific printing technology within the AM process, abbreviated 3DP. AM is therefore a clearer definition which describes multiple processes that selectively deposit material to obtain a desired geometry directly from 3D CAD data. Besides Subtractive Manufacturing and Formative Manufacturing, Additive Manufacturing is the youngest technology. There are many terms used to describe individual AM technologies. Examples of keywords used are “additive”, “rapid”, “layer”, “digital”, “direct” and “3D”. This can become confusing, and multiple processes are known under different names (Gebhardt, 2011, p. 2).

However, Gebhardt and Hötter (2016) presume that Additive Manufacturing, which is standardised in ISO/ASTM 52900 and VDI Richtlinie 3405, will be replaced by 3D printing for a better understanding by the public. In order to distinguish the technologies in this research they will always be referred to as Additive Manufacturing, and 3DP will be used for the specific process.

Besides the different printing principles, there is difference in printers. There are personal 3D printers (fabbers), professional 3D printers or office printers, and there are production 3D printers (Gebhardt & Hötter, 2016, p. 16).

Table 5.1 shows the characteristic process properties of the seven main AM production categories. Most materials can be processed with an AM process. Some of them can be used in pure form in an AM process, others in combination with a binder agent. While ASTM divided the technologies into seven process principles, not all technologies listed in one category share all characteristics. The next sections describe the categories in more detail and focuses on the bandwidth of the main characteristics. Table 5.2 shows how the different AM categories are utilised, and how the different categories can be compared in relation to the material depositioning mechanism.

Table 5.1 Set-up comparison of AM categories

	binder jetting	powder bed fusion	material jetting	material extrusion	direct energy deposition	vat photo-polymerisation	sheet lamination
materials	metals, ceramics, polymers, composites	metals, ceramics, polymers	polymers	metals, ceramics, polymers, composites	metals	ceramics, polymers	metals, ceramics, polymers, composites
type of raw material	powder	powder	liquid	paste, melted materials	powder	liquid	sheet material
support material	yes, the unbound material acts as support material	yes, the unbound material acts as support material	yes, an additional material can be used as support material	yes, the extruded material itself or an additional material can be used as support material	not common	yes, as a space frame truss, often in combination with a raft	no
resolution	high - low	high - low	high - medium	high - low	high - low	high - medium	high - low
internal voids	only if there is an opening to allow unbound material to be removed	only if there is an opening to allow unbound material to be removed	can be realised in closed geometries	can be realised in closed geometries	can be realised in closed geometries	can be realised in closed geometries	can be realised in closed geometries
colour	all colours	material colour with additional pigments if desired	material colour with additional pigments if desired	material colour with additional pigments if desired	material colour	material colour with additional pigments if desired	material colour with additional pigments if desired
multi colour	yes	no	yes	yes, by use of multiple nozzles	no	no	yes, if the sheets are printed before added on top of each other
related classic processes	gluing	laser melting	material spraying	extrusion	welding	photochemical reaction	gluing, stacking

A distinction can be made between printers that are based on a bed of material and those that apply and bind a material by use of an extruder.

Table 5.2 Process and manipulator type

	material bed based	material depositioning by extruder
	powder bed fusion photopolymerisation binder jetting sheet lamination	material extrusion material jetting direct energy deposition
fixed gantry setup	yes	yes
robot arm	partially, but the print bed needs a separate layout	yes
curved print bed	no	yes
print on semi-finished product	only on a flat surface of the semi-finished product	yes

5.1.1 Binder jetting

Binder jetting is an AM technology that selectively hardens a powder. On the building plate, a layer of granular material is deposited and spread by use of a squeegee. A print head moving over the powder material deposits a binder agent at predefined locations of the powder bed to bind the material (Redwood, B., Schöffer, F., Garret, B., 2018, pp. 111-112). The type of binder differs with the printed material. After the binder has been applied, the next step is to lower the print bed, and a new layer of material is applied, where after the material is selectively bonded on top of the material underneath. This can be attached to the layer underneath, but also be the first layer of material that solidifies at this location of the print. In that case, the unbound material underneath functions as a support material. After the print is completed, the unbound powder must be removed and can be reused. While the powder is also the support material, all closed voids in a geometry will stay filled with unbound material. The materials that can be processed are metals, ceramics, polymers, and composites.

Binder that contains pigments can be sprayed on the powder. Such pigments can be used to realise full colour prints. Printing on semi-finished products is theoretically possible but the surface has to be flat. The print bed's surface is limited to a flat surface since the layers of material need to be applied equally over the surface below.

Powder bed fusion is similar to binder jetting in that it also uses a granular powder. Instead of using a binder agent, heat is used to fuse the material particles together. Unlike with binder jetting, prints with multiple colours cannot be realised with powder bed fusion. The colour of the powder will be the final colour of the print.

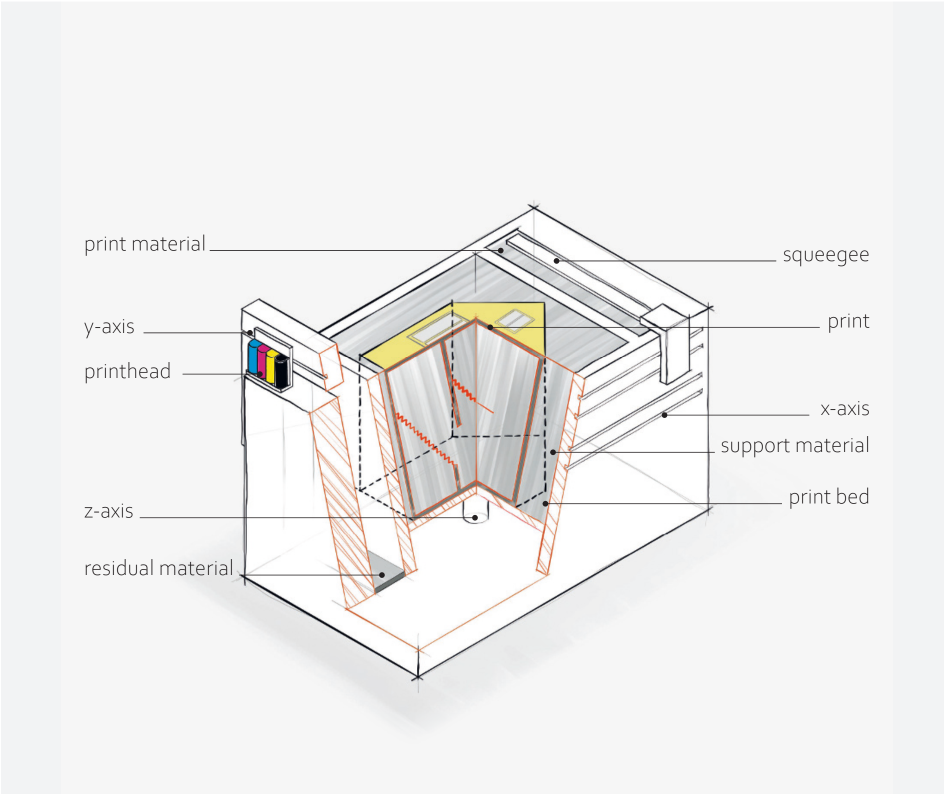

Figure 5.3 Binder jetting

5.1.2 Powder bed fusion

Powder bed fusion is an AM technology that selectively hardens a powder. On the building plate, a layer of granular material is deposited and spread out with a squeegee. A heat source then melts the material and, while it cools, the material solidifies together at the predefined locations (Redwood, B., et al., 2018, pp. 73-74). The heat source can be a laser or electron beam. In the next step, the print bed is lowered, and a new layer of material is applied, where after material is selectively melted. The molten material can be attached to the layer underneath, but also be the first layer of material solidified at this location of the print. In that case, the material underneath functions as a support material. After the print is completed, the unbound powder must be removed and can be reused. While the powder is also the support material, all closed voids in a geometry will stay filled with unbound material. The materials that can be processed are metals, ceramics, and polymers.

Printing on semi-finished products is theoretically possible but the surface has to be flat. The print bed's surface is limited to a flat surface since the layers of material need to

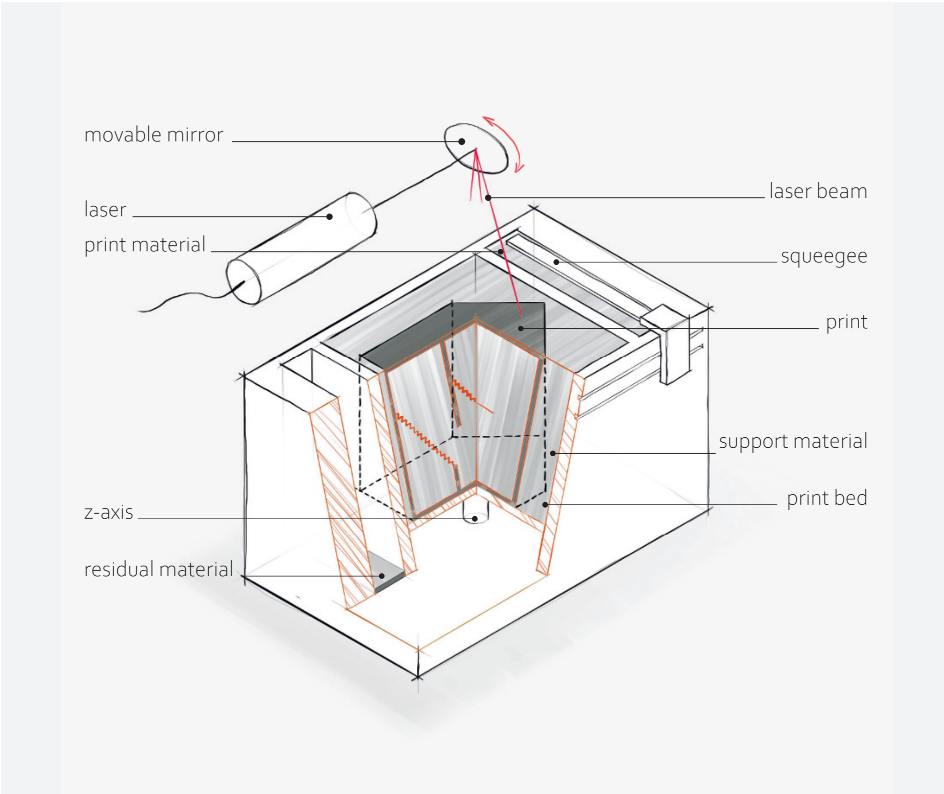

Figure 5.4 Powder bed fusion

be applied equally over the surface below.

Powder bed fusion is similar to binder jetting in that it also uses a granular powder. With binder jetting, a binder agent, instead of heat, is used to merge the material particles together.

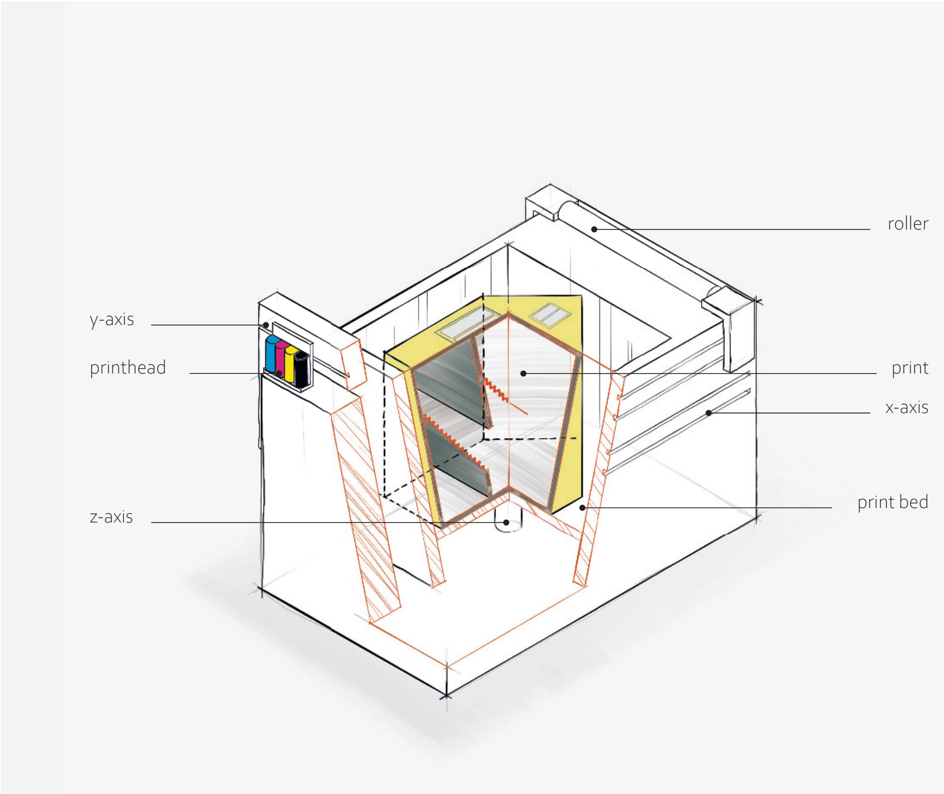

Figure 5.5 Material jetting

5.1.3 Material jetting

Material jetting is a technology whereby material particles are sprayed on the building plate's surface and subsequently on material layers underneath. It can print multiple materials at once, depending on the amount of print heads in the machine (Redwood, B., et al., 2018, pp. 93-94). This technology can therefore be compared to a traditional ink jet printer with additional print heads for different materials, coloured material particles instead of ink colours, and an additional Z-axis.

The material is sprayed on the print bed where after a roller compacts the material. The next layer is printed on top of the first material layer after the print bed has been lowered. This process continuous until the print is finished. The print technology needs to be able to generate support structures to print cantilevers and, therefore, one of the print heads should be processing a support material. In each layer, different materials can be printed simultaneously. Due to the different print heads, a full colour print can be realised and different materials can be combined. When the print is finished it must be removed

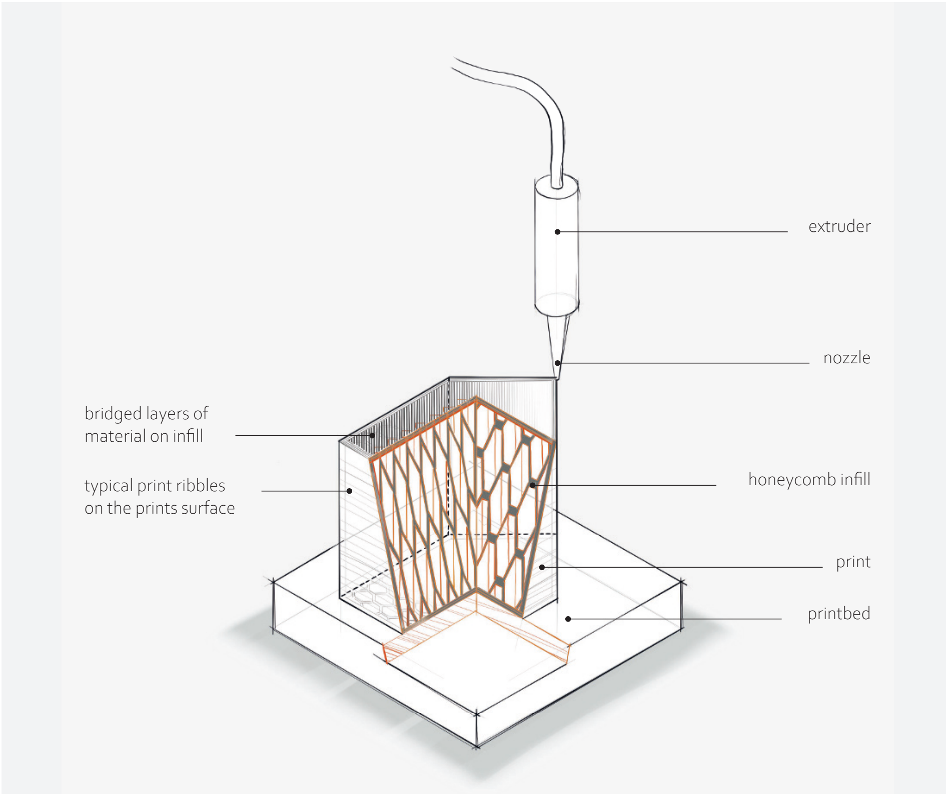

Figure 5.6 Material extrusion

from the print bed and support material needs to be removed.

Material jetting is often utilised in a 3D printer with a gantry and a building platform that lowers each layer. However, the nozzles could also be attached to other manipulators, e.g. a robotic arm. The gantry is highly accurate, which means that with material jetting, the accuracy of a robot arm must be guaranteed. This could allow for an increased freedom in form and control of the layers of material sprayed on top of each other. Ceramics, polymers, and composites can be printed with material jetting.

5.1.4 Material extrusion

The AM technologies based on material extrusion are most commonly utilised in desktop AM. The technology is based on extruding paths of material by use of a material mixture that is extruded through a nozzle (Redwood, B., et al. 2018, pp. 27-28). This material can be liquefied by heating it before it is processed in the nozzle, but it can also be a highly viscous pasty material. In both cases, the material solidifies and will need to have a green strength to support the following layers printed on top of them. Cantilevers can be printed to a certain extent, depending on the material. Larger cantilevers can be realised if support material is used. The support material could be an additional structure with as few points as possible touching the layer of the cantilever element because they are often the same material. If a different, removable material is used as support material, it can be removed easier, by dissolving for example, from complex geometries after the model has been printed. If a different material is used, a second extruder is needed.

The printed model itself can have a solid infill or a partial infill. The amount of infill can be adjusted to the structural need. For non-structural components, honeycomb or similar structures are often printed inside to reduce printing time and weight of the final object. These structures constitute lost support material insides the element. Bridging allows to print across the cavities in the infill and realise a closed layer of material on top of the infill. The amount and span width of bridging depends on the viscosity of the extruded material.

The materials that can be processed in the material extrusion category range from polymers and ceramics to composites. The control of the flow and the solidification process are important process parameters that will influence the print quality. The print bed size is not limited to a certain form or size and the nozzle can describe a path that is only limited by the freedom in movement of the manipulator. In comparison to powder bed technologies, where a flat surface is needed, material extrusion is more flexible and the manipulator could be a robotic arm.

5.1.5 Direct energy deposition

Direct energy deposition uses a heat source to melt i.e. liquefy the material just before it is applied on the print bed or underlying layers of the print (Hopkinson, N., Hague, R.J.M. & Dickens, P.M. 2006; p. 67, Redwood, B., et al., 2018, p. 21). The material fuses together and after cooling down, it is relatively stable. Although it is mostly used for metals, polymers and ceramics can be processed with this technology, as well. If cantilevers are printed, support material might be needed.

The support material is printed with the same material as used for the printed model. The print bed is often at a fixed position, while the print head itself moves in the X, Y, and Z direction. Even though most print technologies print on these print beds, direct energy deposition shares many process characteristics with welding which allows for semi-finished products to be used as a the “print bed” while their geometry is complemented by the printer. The semi-finished product’s surface needs to be prepared to be printed on and the exact dimensions and relative position need to be known.

The difference to material extrusion is that the material is not heated or melted by the nozzle, but by a separate energy source. It is comparable to TIG welding whereby the filler

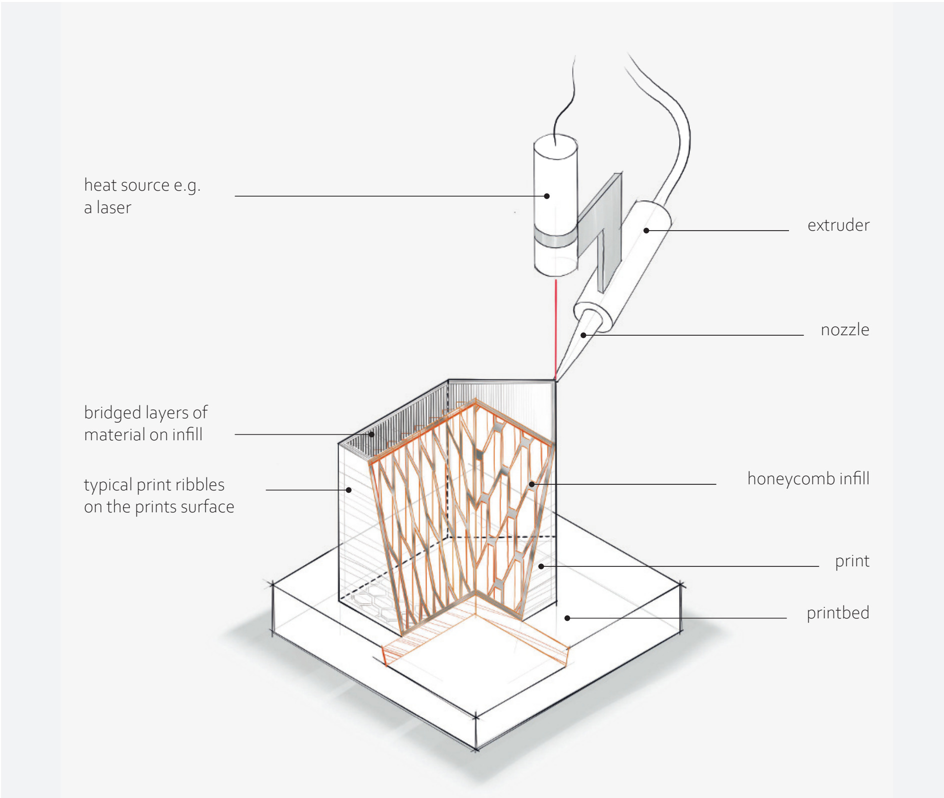

Figure 5.7 Direct energy deposition

rod is melted. The material is solidified when it cools down after it has been deposited at the desired place within the build volume of the 3D printer.

5.1.6 Vat photopolymerisation

Vat photopolymerisation uses UV light to harden a liquid polymer at the desired positions. This technology often uses a building plate that is upside down. The liquid material solidifies if it is irradiated by UV light (Redwood, B. et al. pp. 53-54). By moving the building plate into the liquid, leaving a very thin layer of material in between the building platform and the bottom of the material container, the liquid can be selectively hardened. The bond between the building platform and the first layer is important to avoid de-lamination, causing the model to fall off the building plate during the printing process. After the first layer, the building platform with the first layer is lifted and repositioned slightly above the bottom of the material container to generate a thin layer of new liquid material

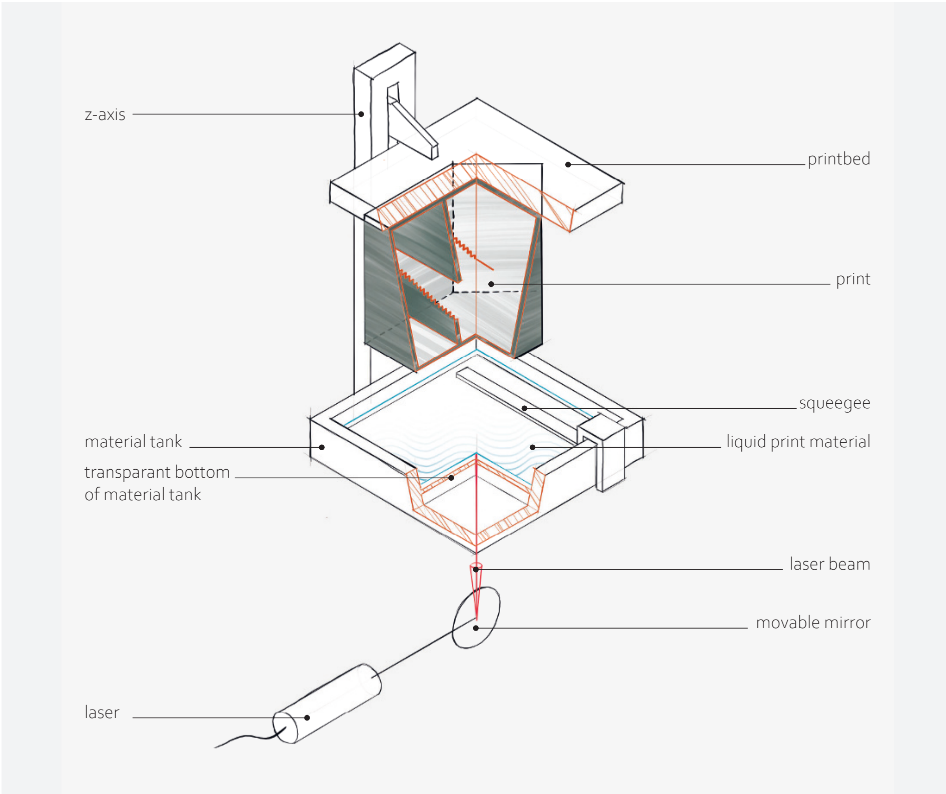

Figure 5.8 Vat photopolymerisation

between the material container's bottom and the first printed layer. The process of UV curing the material, lifting and repositioning the building plate is repeated until the 3D part is finished. Many machines will print a support structure that needs to be removed afterwards. This is necessary because the liquid itself cannot act as a support material.

Due to the upside down position of the build plate, the support material printed is different compared to other AM technologies. The support structure is not a thin walled geometry that should withstand compression forces and could suffer buckling; rather, it often consists of a network of thin tension rods and compression rods that form a space frame truss. Software creates the needed support geometry and raft, helps determine which settings are favourable, and often allows for manual overrides to control what the support material is attached to. The model is often printed upside down to reduce the amount of support material; however, printing the object at an angle provides the best surface quality which in turns means that more support structure is needed. When the print is finished, the support structure needs to be removed and the model needs to be cleaned. Often, the attachment points are still visible but they can be easily removed by sanding.

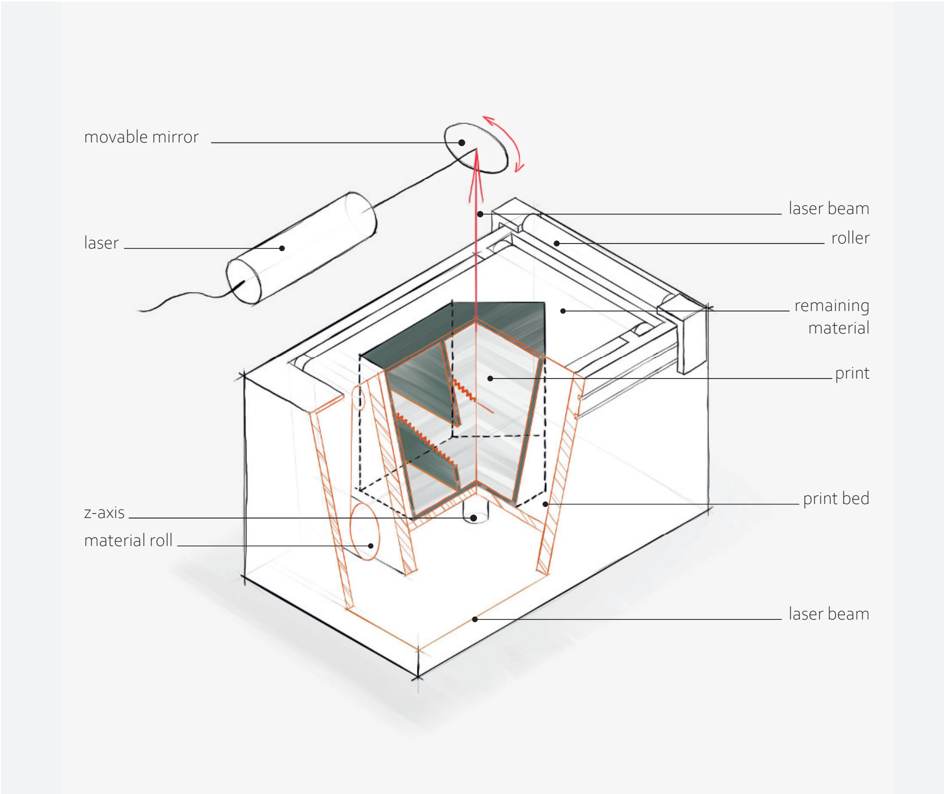

Figure 5.9 Sheet lamination

There is a wide variety of polymers available that can be used for this process. Even mixtures of other materials within a polymer resin can be printed. The mixed materials allow to print ceramic parts, for example. While the ceramic is bound by the by UV light hardened polymer, it will shrink during firing because the polymer will be burned away.

The size of the printed part and print bed are limited to the machine's size and cannot be extended easily. Printing on objects is theoretically possible, but the initial surface should be flat and it should be able to be installed on the print bed.

5.1.7 Sheet lamination

Sheet lamination is an AM technology that places layers of material in the form of sheets on top of each other (Hopkinson N. et al., 2006, p 78; Redwood, B., et al., 2018, p. 21). The process uses sheets that are cut in the desired shape of the layer of the model they represent, with a laser, for example. The first layer of material sticks to the print bed, which is then lowered by the thickness of the layer. The 3D part is built by gluing the sections represented by the sheets of the design together and full colour prints can be realised. The edges of the layers and the outside facing layers can be pre-printed.

In combination with a building plate that can be adjusted to a desired curvature, curved sheet lamination can be achieved with this technology. This results in a more efficient printing process regarding material usage for an arc structure.

5.1.8 Post-processing and hybrid technologies

3D prints have a certain quality and, depending on the application, post-processing is needed. Post-processing can be divided into chemical or mechanical post-processing.

Examples of chemical post-processing are dissolving the outer surface for a smoother surface, or infiltration of the printed object to increase stability and density. Therefore, firing of clay green bodies can be considered post-processing, too.

Examples for mechanical post-processing are sanding and milling. There are also hybrid manufacturing technologies. Mechanical post-processing is integrated into certain AM processes, taking place between printing the layers. In this case, welding and milling, for example, occur within the same CNC process. This is realised by use of two manipulators within the production unit, or by use of a tool-changer.

5.2 AM used in the built environment

Although the building industry is considered conservative (Strauß, H., 2012, pp. 20-21), it has adopted AM over the last decade (Knaack U., Klein, T., Bilow. M., & Auer, T., 2007, p. 126). The applicability of AM in the built environment has been demonstrated by initiatives that utilise the available AM technologies to produce aluminium (Strauß, H., 2012 p. 116), steel, and stainless steel parts. Printing concrete forms with adapted extrusion (Khoshnevis, B., 2004) and binder jetting printers has demonstrated that it is possible to process this construction material widely used in the built environment. Applications are parts and structures created on-site that are used within the building structures and façades. This paragraph describes the development of AM for the built environment.

Common production processes used in the construction industry are welding, milling, stacking, nailing, bolting, gluing, extrusion, moulding. These technologies have evolved over centuries and have been adapted to the need of the different industries. AM does not have a history in the construction industry and has to be utilised before it can be fully adapted to all needs.

AM has evolved over the last decades after its invention in the 1980's. Since it was initially intended to make smaller objects, it did not draw attention from the construction industry at the time. Gartner's 2012 hype cycle regarding emerging technology shows an

AM “hype” in that year and expected AM to be at “the plateau of productivity” in 2017-2022 (Gartner, 2012). The building industry started to pay attention during this peak in 2012. Backed by a growing motivation to utilise new production technologies, AM shows a lot of potential, since all shapes and forms an architectural designer can envision can, at least in theory, be realised. With AM, complex internal structures can also be realised, which opens up possibilities for integrated building physics and optimisation.

Although each building is individually designed and, regarding the design of individual connections and critical details, has a lot in common with a prototype, the market and clients still see buildings as mass produced products. Therefore, the majority of the market will not invest in individually designed products to the same extent as in certain consumer products. Meaning that, during the initiation of innovations, in the building industry it is more difficult to afford the use of exotic and expensive production technologies and materials.

Although not widely utilised in the built environment, AM is broadly applied in other industries. If mass produced products like a car, for example, become more fuel efficient by the use additively manufactured parts, the economic benefit of such an investment can be calculated and earned back during the user phase (Beukers, A & van Hinte, E., 1998, p. 65, Beukers, A & van Hinte, E., 2005, pp. 15-19). Because AM facilitates freedom of form at no extra costs, the building industry can benefit since almost every project is a one-off. Nevertheless, the variety in buildings will cause the design part, including testing and calculations of structural parts regarding strength and efficiencies, to come with an investment for each individual project.

To implement AM parts in the building industry, the market has to be analysed. In the engineering industry there are many examples where AM is used. A first selection of product types that would generally benefit from an AM process are:

(1) Individual complex forms that cannot be made otherwise (Gibson, I., Rosen, D.W. & Stucker, B., 2010, pp. 8-11)
(2) Standardised complex forms that cannot be made otherwise
(3) Small batch sizes which are cheaper to make by use of AM than with conventional production methods (Redwood, B. et al., 2018, p. 9)

These categories can be found in the construction industry, too. In addition, there is a category of products carrying “the first of” in their names. These products are often made specifically for the purpose to utilise AM and to show the capabilities of the technology. AM be can implemented in the built environment in the form of prefabricated parts, or as an on-site production technology. The resolution of the material deposited versus printing speed plays a role in the technology, as do the location of production and the need for post-processing. As not all AM processes are the same, not all AM production technologies are beneficial for the same purpose, making it not just one manufacturing technology but a group of which to chose from.

In the meantime, a variety of research on AM for the built environment has been conducted. Materials like steel, aluminium, plastics, rubbers, ceramics, and even glass are looked at. Next to the difference in material, a distinction can be made based on where the production takes place. Some concentrate on on-site production, while others are using a controlled indoor environment to produce components that are installed on-site afterwards.

While the latter mainly focusses on higher performance parts, the on-site production method seems to focus on large free-form building parts without the need of formwork. Examples are extrusion processes such as Contour Crafting (CC) for concrete by Prof. Dr. B. Khoshnevis and arc welding robots for processing steel.

In comparison, high resolution steel parts are often significantly smaller and produced in a controlled environment. The technique and the material used for these processes have a large influence on the production location due to conditions regarding material storage. Although processes and production methods change, transport will be an important factor in the building industry for the decision making where products should be fabricated or are ordered from.

Since AM is a production process that allows shapes and forms that cannot be made with existing technologies, there is no need for traditional formwork. This advantage makes it possible to produce special forms and customised products that would otherwise not be considered an option in small batch sizes, since the formwork would be too expensive. There is a performance related and an economic motive to use AM.

5.3 AM of clay ceramics

In pottery, it is common to add material while shaping the material by hand. The bound between the different pieces of material is important. It is common that the surface area is roughened to increase its surface area and to realise a better bond (Hooson, D & Quinn, A., 2012, pp. 117, 140).

AM is a digitalised and automated manufacturing process based on adding material layer by layer on top of each other. This is achieved by slicing the digital design. The final planes are parallel to the model printed. Another method of slicing is to generate continuous paths. These paths are not limited to parallel planes, but describe a continuous 3D line.

Robocasting is an extrusion technology (Cesarano, J., 1998, p. 133, Deckers, J., Vleugels, J. & Kruth, J.P., 2014, p. 246) that is used to make free-form decorative items from silicate ceramics. Robocasting can use a continuous path.

By use of the process 3D printing (3DP), a powder is selectively bound using a binder agent. Powder bed fusion relies on stacked layers of powder of which an amount of material is bound together during the production process.

The traditional production processes of processing clay have improved over decades.

Figure 5.10 Free-form object printed by Erno Langenberg
Image by U. Knaack

But even though AM with clay can produce free-form bricks, it is not widely used for the purpose but rather for art and free-form consumer products like vases etc.

Chapter 6 shows more information on the way that ceramic products could benefit from an AM production process.

5.4 Research projects

Research has been carried out on AM of clayey ceramics, mainly on binder jetting for sculptural forms and extrusion of a highly viscous clay paste. But at the time that this research project was initiated, strength tests and research on how to comply with building regulations were not yet presented.

Before the according machines were available, researchers experimented with experimental extruding set-ups or adapted selective binding or sintering printers.

(1) Professor Ganter, University of Washington, started to print with ceramic powder and a binder at his institute in 2009.
(2) At the Bowling Green State University (BGSU) professor Balistreri works with a binder jetting machine, as well, and claims to reduce the shrinkage in his US patent US8,568,649 B.
(3) In Bristol, United Kingdom, at the University of the West of England, a research collaboration using 3DP took place (Huson & Hoskins, 2014, p. 354).

Figure 5.11 Free-form elements in a “room divider” printed at the University of Minho in Portugal
Image by U. Knaack

Figure 5.12 Free-form ceramic
Objects printed by the Fabrication and Material Technologies Lab at The University of Hong Kong
Image by U. Knaack

Not all AM technologies can be used for clay-based ceramics. The technologies used to demonstrate the AM of clay are:

(1) Binder jetting
- 3DP Ink jet (Huson & Hoskins, 2014, pp. 351-354)

(2) Material extrusion
- DIW, FDM, Robocasting (Carter & Norton, 2013, p. 431)
- Robocasting by P. Cruz at the University of Minho, Portugal (Figure 5.11)
- Robocasting by E. Langenberg (Figure 5.10)
- Robocasting by C.J. Lange at Hong Kong University (Figure 5.12)
- Robocasting at the Royal Danish Academy

(3) Vat photopolymerisation
- SLA (Carter & Norton, 2013, p. 431)

(4) Powder bed fusion
- SLS (Klocke & Ader, 2003)

There have been some initiatives on clay printing, most of which focus on sculptural freedom, especially after the clay printers – similar to a desktop extrusion printer – became available. These robocasting printers, based on the extrusion of a paste, are used by research institutes worldwide. A. Wolf et al. (2021) have listed many initiatives in a paper on state of the art AM for ceramics. Silicate ceramics are used in many buildings. When produced with an robocasting process, the product characteristics will change as well as the main characteristics but the material itself will not – to the utmost extent.

Binder jetting seems to be the most accurate production technology used in those early research projects. Still, the additively manufactured products made by binder jetting exhibit higher contraction and distortion during firing than traditional pottery. The strength of the fired product is lower and the porosity higher, making them vulnerable in everyday use (Huson & Hoskins, 2014, p. 355). With a material extrusion process, the products are less porous since no binder material is extracted during firing, but the resolution is significantly lower. Examples can be found in the early work of Prof. Khoshnevis and that of E. Langenberg (Figure 5.10). Each with different reasons to use ceramic material, both showed that the extrusion technology had potential to produce free-form objects with a high viscosity pasty material.

The aforementioned initiatives show the first additive technologies that can be used to print clay ceramics. However, there are also technologies used to print technical ceramics, which could be used to print silicate ceramics, but need to be adapted. There is a difference between those that only use a binder and those that do not. In case a binder is used, a mixed material will be the result that can be post-processed. During post-processing, the material can be dissolved or burned away. There will be porosity, and this can be infused by changing the material mixtures. The possible technologies to process ceramic material are:

(1) Binder jetting
(2) Extrusion
(3) Powder bed fusion
(4) Photopolymerisation

For processing silicate ceramics, the first three categories of AM have been used by research initiatives. Photopolymerisation is used for technical ceramics.
For many materials processed with AM, the complete process chain changes. For clay parts produced without a direct sintering method, the parts are only shaped with AM. The steps for clay processing, such as drying and firing afterwards, still need to be performed on these additively manufactured green bodies.

In the silicate ceramic material, the molecular alignment changes during firing. It makes the material stronger but also causes additional shrinkage that can differ in X, Y, and Z direction. Special attention needs to be paid to reduce internal stresses that could cause cracking of the material. There are many parameters that influence the quality and performance of the final product.

Compared to traditional clay production technologies, AM can be used to only replace the shaping part in the production chain. Although it only replaces the shaping part it influences the final characteristics of a product due to the layered nature of this production process. Replacing only one step in a production chain makes the AM technology less complex. Compare it to AM of materials whereby the chemically-induced hardening of the material is initiated during the AM process, not allowing for additional post-processing between shaping and hardening. Drying and shrinkage need to be controlled after printing clay in a controlled environment.

To minimise the influences of AM shaping, there are process parameters and steps that can be taken into account. These steps in the AM production process are causally related to the process selected. For ceramics, the production steps that are influenced by the technology and therefore influence the final product are the:

(1) Design
(2) Production method and approach for fabricating
(3) Material
- Composition
- Grain sizes
- Behaviour of the material regarding shrinkage
- Behaviour of the material regarding firing

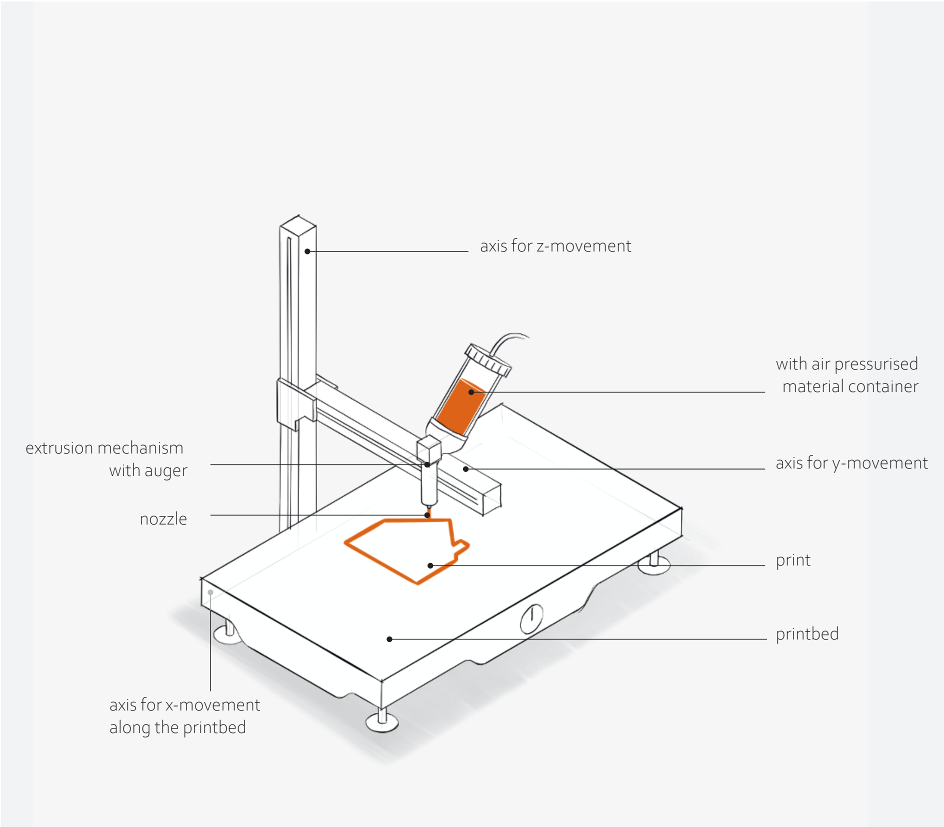

Figure 5.13 Principle of desktop robocasting

5.5 Preliminary research and potential of additive manufacturing of clay

In 2015, the Institute of Structural Mechanics and Design in Darmstadt made the decision to start printing silicate based ceramics for building products; a decision that spurred this thesis. The focus lies on the printing technology, the materials, and the influence of both on final building products. Concepts on additively manufactured products made of silicate ceramics to be used in buildings already existed, but non of the researches took the complete production chain, from raw material to product, into account.
Various bricks were printed to obtain the characteristics of the first desktop robocasting utilised in the preliminary phase of the research. Figure 5.13 shows the principle of the desktop robocasting printer used in this preliminary research.

Figure 5.14 First free-form bricks printed at TU Darmstadt
Institute for Structural Mechanics and Design

5.5.1 The printer setup

The robocasting printer used in the preliminary research is an extrusion-based 3D printer that can process a pasty silicate ceramic material. The printer was one of the first (serial no. 007) built by the Dutch company VormVrij. The mixed, high viscosity silicate ceramic material is fed in the material container and extruded with air pressure and the rotation of an auger in the nozzle. The building plate of the printer was 60 x 70 cm and the height of the Z-axis was 55 cm.

The printer was equipped with different material containers. Large containers were placed above the printer and the material was fed to the extruder through a hose. Smaller material containers were mounted directly on the extrusion mechanism. Mounting the material container directly on the extruder eliminated the friction resistance of the material in the hose. It was possible to print with a less plastic and more stable material mixture; however, the amount of material in the smaller container reduced the size of the prints significantly. The printer could not change material cartridges and return to the position where it stopped since the software did not allow for such machine movements.

The printer had two nozzles, allowing for dual material printing. Different material mixtures could be used within one print by utilising this feature. However, this could only be used with the larger containers, since the smaller containers did not fit next to each other on the printer due to a lack of clearance or alignment of the material inlet of the extruders. Utilisation of two nozzle reduced the print bed size in Y direction due to the

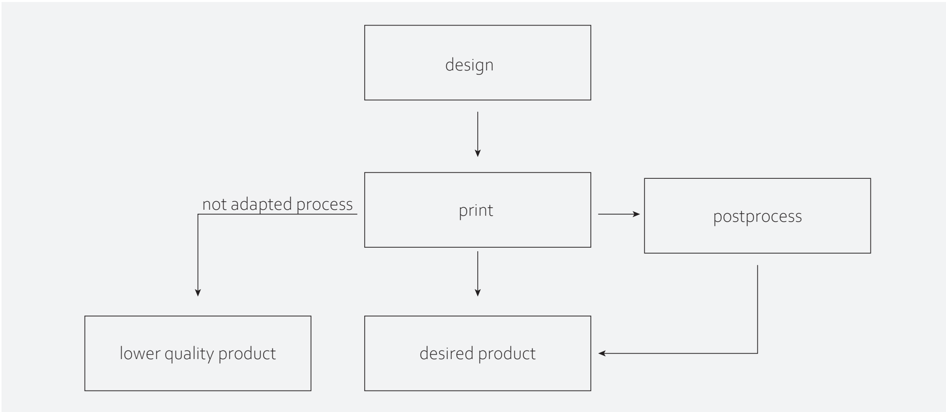

Figure 5.15 Printing principle with post-processing

offset of the nozzles in relation to each other.

5.5.2 Operating the printer

Before a model was printed, a G-code needed to be generated. This G-code describes the paths and the amount of extruded material. The material needs to be mixed and a material container has to be filled with material by hand. While preparing the material and filling the material container it is important to prevent the inclusion of air pockets in the material. After the material container was filled, a plastic ring was placed on top of the material. This ring distributes the air pressure onto the material, but does not seal of the material. The material is therefore not completely separated form the "air chamber" in the material container.

The printer was controlled by a small interface. The interface had a SD card slot, and the programmes with the G-code were stored on a SD card. The print was started and controlled via this interface. The air pressure could be regulated between 1 and 6 bar. Although the printer and G-code define the RPM of the auger, the pressure influenced the amount of material extruded, too.

5.5.3 Challenges in the printing process

The first bricks were printed (Figure 5.14), and the relationship between the printed parts and the adjustable parameters became visible. However, after printing and experimenting with this printer some challenges became visible, as well. Figure 5.15 shows a schematic relationship of the influence of a printer on the quality of the printed design.

The advantage of the simple layout of the utilised desktop printer is that the parts of the printer that caused the challenges could be changed. Even though some flaws were not solved at the time, the resulting prints showed the potential that initiated this research. The flaws can be categorised as flaws related to the material, the engineering quality of the machine, and to external influences like humidity and temperature. These flaws were:

(1) Air inclusion in the system
(2) Plasticity regarding stability of the print and the extrudability of the material
(3) Accumulated heat (increased temperature due to surrounding temperature and friction)
(4) Accuracy of the print
(5) Asymmetric drying

Air inclusion in the system

Air inclusion in the material is caused by the mixing of the material and by flaws in the machine. The most visible flaw was that before the material barrel is empty, air could get passed the plastic ring. While the friction of the material is overcome and the air travels through the voids, since they constitute the least resistance, the air will escape through the nozzle. The force of the air then damaged the printed parts. This flaw happens because the material container is designed without a gasket. Also, when the plasticity of the material was too low, the material clogged the mechanism and the printer drew air through the gaskets in the extruder. This caused interruptions in the printed paths, due to a material supply shortage.

Plasticity regarding the extrudability of the material

The plasticity of the material is determined by the material mixture. However, the fact that the plasticity of the material influenced the prints was caused by the extrusion mechanism and the printer layout. The friction between the material and the wall of the material container decreases during the printing process, while the amount of material in contact with the wall also decreases. This causes the pressure at the inlet of the extruder, at the location of the auger, to increase. The layer thickness increased while the auger was fed with more material.

Print accuracy

The accuracy is determined by the stability of the gantry frame and the stepper motors. Due to the weight and unstable gantry frame, the deflection of the beam which accommodated the Y-axis changed during the print when the small material container was used.

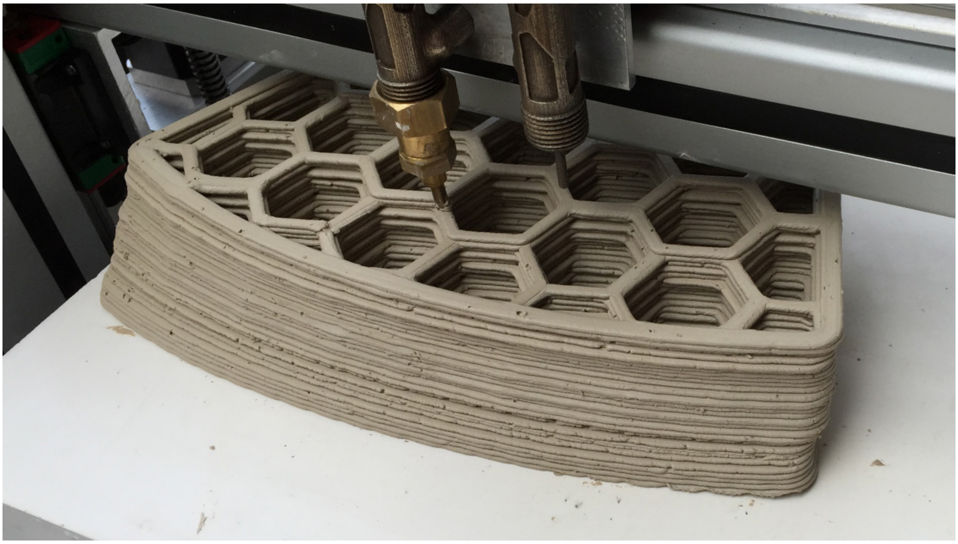

Figure 5.16 Inaccuracy of applied layers
The manipulator used was not accurate at higher print speeds.

Figure 5.17 Accurately applied layers

The more material in the container, the more weight and deflection. When the weight reduced during the print, the deflection decreased and the top of the printed layers became more parallel to the building plate. While a material change was not possible with the interface, the changing deflections would have hindered the implementation of this anyway.

Figures 5.16 and 5.17 show the influence of the print movement speeds of the desktop printer. The printer has a maximum print speed at which the path is accurate. If printed faster, the print path becomes inaccurate (see Figure 5.16).

Heat accumulation

Heat is introduced into the printing process by the ambient temperature, but also by friction in the extruder. In the extruder, before the auger, heating elements with sensors were installed to heat the material before extrusion. In theory, this should allow for the extruded material to dry quicker; however, it seemed that it already dried the material in the extruder and nozzle, thereby reducing its plasticity. This was possible because the gaskets did not prevent air to be drawn into the system and moisture could evaporate while the material was being heated. This resulted in clogging of the nozzle.

Asymmetric drying

The fresh extruded layer has a higher water ratio than the dried layers. This can introduce stresses when the geometry of the newer layer adapts/fuses together with the shrunken geometry of the layers below. Due to shrinkage during drying it is important that all parts of the print dry at the same speed. If the drying process is "asymmetric", internal stresses in the print occur. The drying process can be controlled by the geometry, or postponed by a relatively high humidity in the print chamber. An increased airflow across the printed part can increase the speed of drying. This increases the stability and green strength of the printed layers, but makes the drying process asymmetric. This issue has only been noted, and more experiments need to be carried out to verify which drying speed is desired during the printing process.

To reduce the influence of asymmetric drying, an initial step could be to lower the water ratio in the printing material, because reducing the amount of water in the material means a reduction of shrinkage. Plasticizer can be used to lower the water ratio and maintain the plasticity of the clay mixture.

5.5.4 Process optimisation

An improved replicability is a result of improving the before mentioned production process parameters. Therefore, the material and the stability of the printer were adjusted during the preliminary research. However, not all flaws could be eliminated. The heat due to friction, for example, could not be prevented. The sealing mechanism was not functioning; it not only drew air, but it also could not always cope with higher internal pressures, and started leaking material. The air inclusion in the print could be minimised but not eliminated entirely because there also was some air leakage from the gaskets in

Table 5.3 Technical SWOT analysis of the desktop robocasting printer

internal	strength	weaknesses
	- accessible - relatively cheap - easy to use - large building volume for a desktop printer - can process a variety of materials - can be used as an experimental setup in research projects	engineering weaknesses which result in: - air inclusion - clogging of the nozzle - influence of the air pressure on the printing quantity - instability of the gantry - not as plug and play as 3D printers for other materials on the market - larger chamotte cannot be processed - cartridge change is not available during print, making it hard to print larger objects - needs constant monitoring
external	**opportunities**	**threats**
	- the printer can be adapted and improved due to the open source setup - the relative new technology can fulfil the demand of the market to make a variety of new products that cannot be produced with standard processing methods	- dependency on environmental conditions while these influence the print quality this results in: - changing overall extrusion quality - asymmetric drying

This SWOT analysis is based on the experience and assessment of one of the first Vormvrij Lutum printers used in the preliminary research. This assessment has been made as input for redesigning and adapting a print process for clay and is not a review of the printer.

the system.

The material extrusion and amount of extrusion could be improved by using the same material mixtures and by monitoring the extrusion. However, the process did not allow for an extrusion controlled by the revolutions of the servomotor attached to the auger, while the air pressure and internal resistance also influenced the amount of material that was extruded by the nozzle. Therefore, the amount of material deposition could not be fully controlled (Cruz, P. J. S., Knaack, U., Figueiredo, B., & de Witte, D., 2017, p. 5).

Although these flaws make the process seem unstable, the printer did print the first free-form brick. The expectations for this technology are therefore high. What the future will bring depends on many factors, including inspiration regarding the design, but regulations as well. Table 5.3 shows a SWOT analysis of the robocasting technology in the desktop printer used in the preliminary research phase.

5.6 Printing for the built environment

Clay is a common building material. Silicate ceramic material has been used over the centuries as a cheap and robust construction material. A higher grade of clay like white ware and porcelain is used for dinnerware, laboratory equipment, decoration, and art, but not for many other consumer products. This is very different from the product made with plastics and alloys. They are used in the largest constructions, but also for very small parts in consumer products.

Directly related to the civil application is the certification of additively manufactured building materials. Since every product can be different, product certification will not be feasible. Process certification that is already used for glass structures may be a solution when final material characteristics can be predicted by use of simulations based on material models.

Nowadays, the brickwork building products are tested by normalised tests described in standards. CE marking of products and a Declaration of Performance (DoP) are used in the built environment, too. Examples of standards on which harmonised technical specifications in norms are based are;

(1) EN 771-1 Specification for masonry units - Part 1: Clay masonry units, series which replaces most German DIN 105 norms (tests apparatus are described in EN 772)
(2) EN 1304 - Clay roofing tiles and fittings - Product definitions and specifications
(3) EN 14411 - Ceramic tiles - Definitions, classification, characteristics and marking

Since safety regulations for civil applications need to be strict, all products, including those produced with a new production technology, need to comply with them. However, AM is not mentioned in these standards.

The production processes for processing clays and other materials are often adapted to the material. While AM is not a defined production technology, the development can advance in three directions:

(1) A process that can process materials as they are now
(2) A process that can process materials that are different from those available now
(3) A changed process and changed materials, both adapted for each other

The next part of the research focusses on the production process and material. Important parameters are safety, durability, and sustainability.

Besides safety, the products and materials used should be durable to withstand external influences and should permit, when applied accordingly, a low-energy and sustainable building. Sustainability is not limited to the energy used in the user phase but also involves the grey energy in the product. For structures, the grey energy has a lower impact due to the expected longer user phase than of products that are not that durable. When a technology for AM of clay is engineered, a future life cycle assessment (LCA) can provide more information on the performance of these printed bricks regarding energy usage.

Part II

This second part of the research focusses on the application and engineering of an AM technology to process silicate ceramics (clay). The aim is to answer the research questions that involve: what could be printed; how could this be printed; and how do printed parts perform. A design study focussing on clay products that can be made with and benefit from the use of a 3D printing technology is presented in Chapter 6. Results of this design study are selected and used to define parameters to select a printing principle. The principles and properties of the printing processes that have been listed and described in Part I will be evaluated in Chapter 7. Based on their properties and using the parameters defined, the best matching principle is selected for AM of clay in Chapter 8. While clay is a natural product, the composition of different mixtures varies and a fluctuation in material properties can occur even within batches. Since material composition has a significant influence on the printing technology, the material properties are described in Chapter 9. Chapter 10 shows the performance of the first printed samples. How the selected principle will be adapted further to process the clay with a new printer will be discussed in Chapters 11, 12, and 13.

Figure 6.1 London Terrace apartments
Building complex (Farrar & Watmough) seen from W 23rd street and 10th AV - New York City, United States

6 Application

The state of the art of ceramic building components and the processing methods of basic AM principles have been previously described. In this chapter, the utilisation of AM for silicate ceramic (clay) building components will be shown on the basis of the first design ideas for what AM of clays can be used for within the built environment. The state of the art functions as a base and source of inspiration.

Within the built environment, there are many construction principles. Many clay building components are used for low residential buildings and apartment buildings, but ceramic cladding elements are used for highrise and utility buildings. Depending on the structural layout, there are different applicable façade systems.

Moulds can be additively manufactured and used to make free-form objects, but not all forms can be made by using reusable or lost formwork. Printing of formwork is therefore a good tool for making formwork for the classic production techniques (Knaack, U., de Witte, D., Mohsen, A., Tessmann, O. & Bilow, M., 2016, p. 113). Although this strategy has potential, formwork is not part of the scope of this research.

Many functions need to be fulfilled by the façade and the embedded secondary structure (Herzog, T., Krippner, R. & Lang, W.,2016 p. 16, Knaack, U. Klein, T., Bilow, M. & Auer, T., 2014, p. 36). The implementation to facilitate these functions depends on the climate, tradition and available materials (Yanovshtchinsky, V., Huijbers, K. & van den Dobbelsteen, A., 2012 pp. 17-18). While clay products are used in many façades, these products are exposed to external influences and should, therefore, function in the complete system. Figure 6.2 shows a section of a façade and the external influences.

Paragraph 6.3 shows what kind of free-form clay products could be printed for the built environment. These examples are individually illustrated and described. The conditions derived from these examples serve as input for the conditions a print technology needs to fulfil.

Although, generally, ceramics can be formed into almost any desired shape, this is highly limited by the combination of materials and accompanying processing technique. AM offers freedom of geometry. Ideally, any desired form can be printed with AM with one of the printing methodologies. Some post-processing may be needed, depending on the design demands and printing principle used.

Utilising AM to compete with highly standardised technologies, which often produce large batch sizes, is not economically feasible yet. Small batch sizes or individual designs, however, benefit from AM, because there is no need for formwork or other tools that might be mandatory if they are made with traditional production methods. In the built environment, products, i.e. buildings, are realised in relatively small batch sizes, often

D. de Witte, *Clay Printing*, Mechanik, Werkstoffe und Konstruktion im Bauwesen 62, https://doi.org/10.1007/978-3-658-37161-6_6

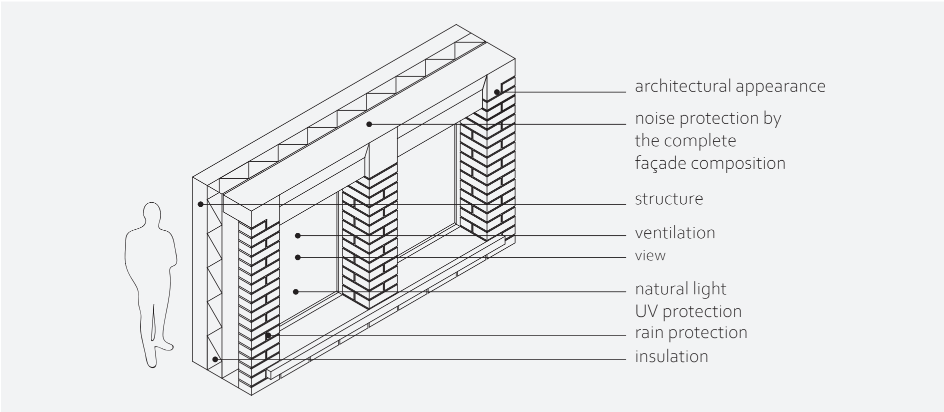

Figure 6.2 Façade functions

assembled from smaller standardised products. In comparison, tableware, for example, is made in large batch sizes and there is hardly any individualisation. In buildings, some of the standard products cannot fulfil all demands and can be exchanged by individualised components, especially at the edges and intersections of components. Looking at brickwork, this is exemplified by corner quoins and keystones in arches. Next to these part designs, which are highly influenced by architecture and aesthetics, components with an optimised inner structure can fulfil demands regarding structural and energy performance (Knaack, U., Bilow, M., Auer, T. & Hildebrand, L., 2011, p. 72) that cannot be fulfilled with traditional processing technologies. Besides the advantage regarding the geometrical freedom in comparison to traditional production processes, it is possible to control the usage of multiple silicate ceramic material mixtures in one design. The materials within such a design can differ in colour and density, but need to share certain characteristics to avoid stresses such as internal stresses inside the part, for example.

6.1 Designs opportunities

A design comes with desired characteristics. These characteristics are related to the product's performance and aesthetics. These, in turn, are influenced by the performance and quality that the chosen production technology offers. Since, in this thesis, no production technology has been selected yet because the goal is to identify a suitable AM production category and related process, the characteristics defined in this paragraph are not limited. Compared to the known surface qualities achieved with standardised production technologies, AM is distinguished by the visible layers of the product if the surface is not post-processed.

Besides freedom of form and the possibility to embed additional functions, there are other categories of products that can be realised. The main difference between an additively manufactured and extruded or moulded product is that the product is made by adding layers on top of each other and that the material addition can be controlled and changed per layer and, depending on the technology, at any position in the print. This can lead to products made of silicate ceramic materials with differing compositions in one print. Therefore, the complete material can be changed during the printing process, so-called multi-material printing, but also the density can be changed to obtain a gradient at different positions in the print, by use of certain technologies.

6.1.1 Multi-material components

If clay ceramic products are made layer by layer, these layers do not all have to consist of the same material. The layers could be printed in different materials, and even gradients would be possible. If multiple material mixtures can be combined, it is not only possible to optimise material usage, but also various material mixtures within the product.

6.1.2 Density-optimised

Theoretically, any AM methodology can be used to realise a density-optimised product by selectively depositing material, but the resolution and possibility to remove unbound material from the created voids varies amongst the AM technologies. Another approach to realise density-optimised products is to print with a support material that can be removed manually or chemically, or by changing the amount and size of used aggregates within the print material at the different locations within the print.

6.1.3 Performance-optimised

Improvements for energetic performance can be obtained if the selective depositioning of material is used to print internal structures that can act as a heat exchanger with the environment and the inside of the building. By realising capillary pipes inside bricks, for example, water can be pumped through the façade. Another approach is to ventilate air through building components which allows for cooling of thermal mass (de Witte, D. et al., 2017, pp. 108-109; de Klijn-Chevalerias, M. L. et al., 2017, pp. 243-244).

Internal structures can also be used to improve acoustics in a building by eliminating natural frequencies in the components or by adding material to reduce amplitudes of predefined frequency spectra. Parametric designs of inner structures can be adjusted to specific needs (Knaack, U., Klein, T. & Bilow, M., 2008, p. 45).

Figure 6.3 Ceramic ornaments Casa Batlló
Antoni Gaudí - Barcelona, Spain

6.1.4 Added functionality

Functional, decorated building parts, i.e. lights and rainwater spouts, window ledges with water drainage, façade integrated benches and bird houses are examples of added functions to standardised products. Even if they are to be used in a product system and the batch size is larger, they can benefit from an AM process if they cannot be made with existing technologies. The complexity in form determines whether or not such products are economically feasible.

6.2 Characteristics

The before mentioned characteristics can be combined into functional parts that do not only benefit from an increased aesthetics and performance but also fulfil new functional demands.

Heavier elements are generally larger than lighter ones. Since such larger and heavier parts are also subjected to all the parameters above, an analysis of how large free-form cladding plates compare to the other characteristics will be described in a separate paragraph. Even though large products are not a dedicated part of this research, the scalability of the printing process is addressed; based on an introduction of the requirements of these larger elements. A so-called resolution size paradox occurs when printing larger

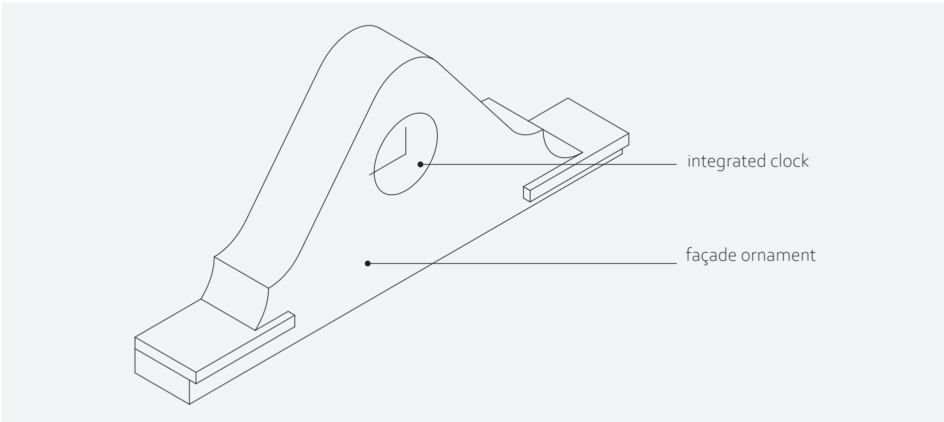

Figure 6.4 Ornaments

elements. The amount of material processed at any given time has to increase to print large elements within a certain period of time. When increasing the amount of material processed without increasing the speed of the manipulator, the resolution logically has to decrease, which results in a coarser print (Buswell, R. A., Soar, R. C., Gibb, A. G., & Thorpe, A., 2007, p. 229).

The products can therefore be categorised according to their application type, weight, and size. Due to building regulations, the ceramic building components can be divided into smaller and larger elements based on the weight that can be lifted at the building site by hand without the use of special tools. Furthermore, ceramic building parts can be divided into main support structural components, secondary support structural components, and non-structural parts. However, most building components can be categorised as both, structural and non-structural, depending on their application. Their role depends on the building's structure, meaning that a non-structural system part like a lintel can be load-bearing even though it is not considered part of the main structure of the building.

Depending on the main structure of the building, bricks can be part of the structure or they function as a shell to protect the structural components. The different construction principles ask for a wide variety of products; cladding panels fit in the latter category, as well. These parts function as a rain screen and fulfil an aesthetic function while other building parts serve as structural components.

However, the functions of a façade are sometimes integrated in a more monolithic façade construction. Such façades are often load-bearing, too. Vertical perforated clay blocks are an example of a clay building product that forms the façade and also has a load-bearing function.

The products used in the built environment have different functions and come with different requirements. These requirements can differ for each design or product.

To select the proper AM principle and to see how requirements can be met, conditions

Table 6.1 Characteristics and requirements of the design

component	category	expected maximum dimensions	material	maximum weight	conditions related to the design appearance
special bricks around window frames	ornamental, integrated functions	25 x 25 x 25 cm	weather resistant	up to 20 kg	resolution, Free-form
special roof tiles	ornamental, integrated functions	25 x 40 x 5 cm	weather resistant	up to 20 kg	surface quality
lintels	ornamental, structural	120 x 20 x 25 cm	weather resistant	more than 20 kg	surface quality
personalised bricks in masonry	ornamental	25 x 25 x 25 cm	weather resistant	up to 20 kg	surface quality
cladding, a variety of bricks and cladding plates	ornamental	200 x 120 x 10 cm	weather resistant	more than 20 kg	surface quality
functional decorated building parts, rainwater spouts	ornamental, added functionality	50 x 40 x 40 cm	weather resistant	more than 20 kg	surface quality
Window ledges	ornamental, added functionality	120 x 25 x 15 cm	weather resistant	more than 20 kg	surface quality
heat collectors	functional part	200 x 120 x 10 cm	weather resistant	more than 20 kg	resolution
structural parts	structural parts	120 x 20 x 25 cm	strength optimised	more than 20 kg	density

for the print process need to be defined based on these requirements. A list of common conditions related to AM clay products is derived on the basis of the desired product characteristics. Table 6.1 also shows the important characteristics of the silicate ceramic building components and formulated conditions regarding the performance of the parts. These conditions are:

(1) Required strength
(2) Surface quality
(3) Dimensional accuracy

(4) Resolution
(5) Surface finish
(6) Durability (Weather)
(7) Optical appearance
(8) Insulation performance
(9) Resistance against weather influences
(10) Colour durability
(11) Freedom of design

Next to these conditions, the digital print file should be one of the standard 3D file types to make the technology widely available. Even if AM as the more expensive technology is the only feasible production method for a particular design, price is still an important parameter, since many building projects undergo cost saving rounds, and omissions or substitution could occur. Therefore, conditions that relate to economic motives need to be added to the list:

(1) Easy file handling
(2) Production time
(3) Price

General criteria are size, weight and whether they are free-form and use one or multiple materials. The different design examples are described individually.

6.3 Printed brick products

Since AM is a different production technology, the product characteristics of AM produced products differ from those made with standard production methods. The layered appearance of additively manufactured is characteristic for the technology. Even though it may not always be desired, it is a surface finish that cannot be produced with, for example, a brick extrusion process. Therefore, the resolution and the visible layers is indeed a design opportunity, in spite of the general tendency to consider it a negative property. Punched bricks (Wasserstrichziegel), for example, are known for their characteristic surface appearance, which also results from the production process.

Additively manufactured products can be post-processed. The outside surface can be milled, but any internal geometry is more difficult to post-process. However, the nozzle can be adapted to facilitate a form of "wet post-processing" by use of small blade knives to smooth the extrusion path.

For each design example, the designer has to decide whether the characteristic production method's appearance are to be maintained or not.

Figure 6.5 Typical brickwork building in Soho
145 Sullivan St - New York, USA

6.3.1 Ornaments

Ornaments can be utilised in building façades. Usually, ornaments are made by hand or by use of a moulding technology, which is very time consuming and expensive for individual parts. AM, on the other hand, is predestined to make individual ornaments. It does not require the batch sizes needed for efficient mould processing. Since AM does not depend on formwork or moulds, the price of a printed part is only influenced by print time.

The important product characteristics of ornaments are surface quality and weather resistance. AM is characterised by the inherently layered appearance of the products' surface. It is difficult to obtain such layered surfaces with traditional processes. The designer can choose whether to retain the characteristic AM surface or to post-process it. The glaze response to the material is important, too. Together with weather resistance, this is largely influenced by the material that is printed by the AM technology. Preferred are dense materials that can be sintered at a higher temperature so that they do not absorb water, because internal moisture could cause damage during the winter seasons.

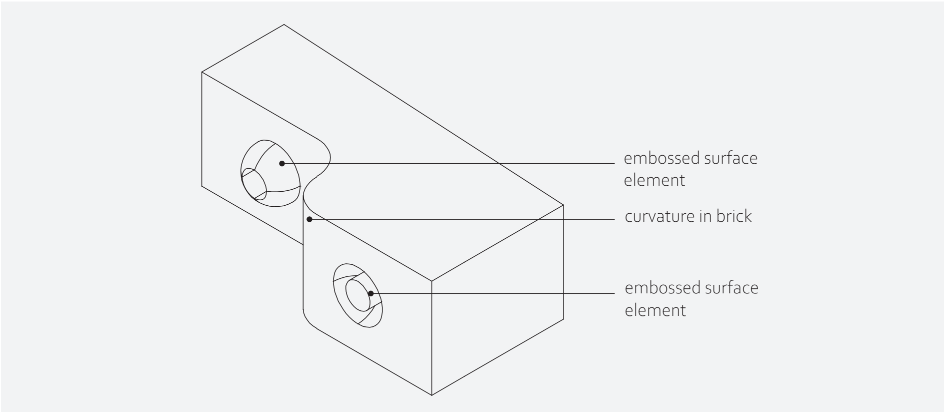

Figure 6.6 Customised bricks in masonry

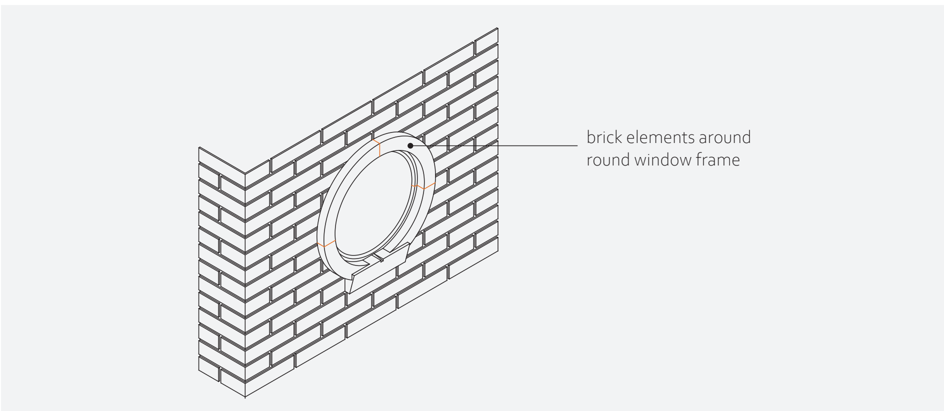

Figure 6.7 Special formed bricks around round window frame

Special bricks around window frames

Special bricks around window frames are typically free-form. They share the same characteristics as ornamental bricks, but the internal structure can help to improve the building's physical performance by optimising the structure to improve insulation around the window frame. Special anchor points can be printed, as well, that allow for a better window frame installation.

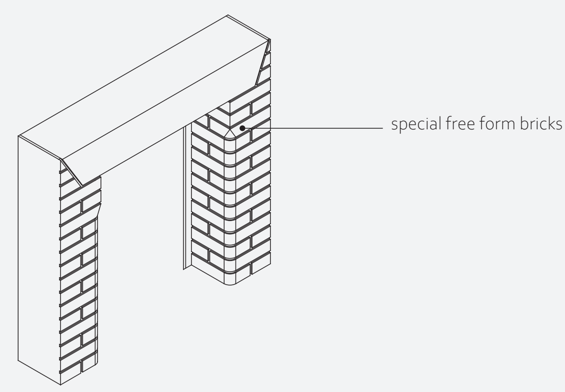

Figure 6.8 Special bricks around window frame

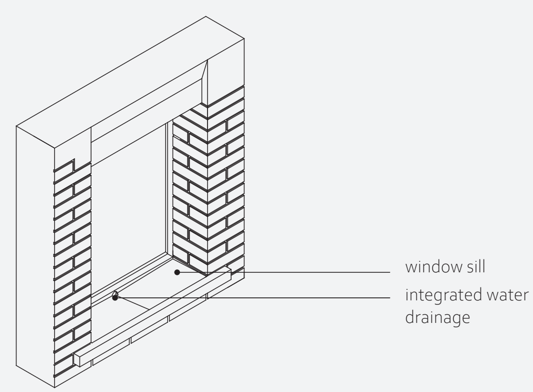

Figure 6.9 Window sill

Window sill

The sill underneath the window can be modified to include integrated water drainage. This will reduce the staining of brickwork around the window and will change the façade's aesthetics. The water drainage can be realised in the cavity of a brickwork wall.

Lintel

Lintels are not only decorative but also structural. They share the same characteristics as ornaments, but are discussed in the next paragraph as an structural element.

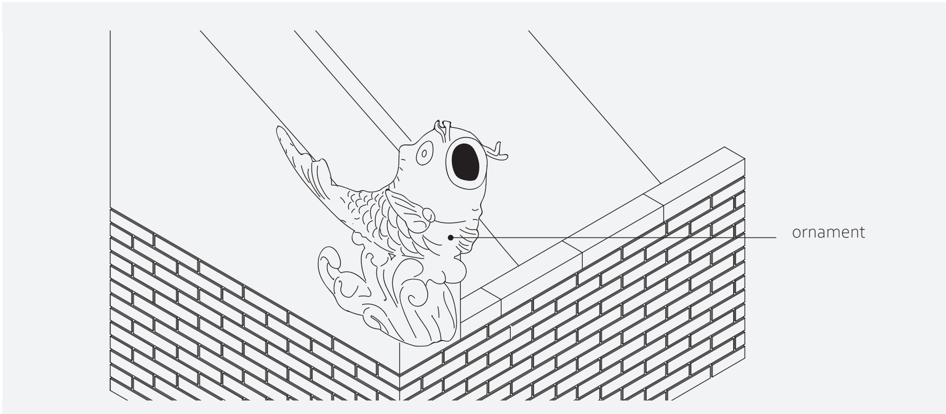

Figure 6.10 Special roof tiles

Special roof tiles

Roof tiles are produced with an automated process. The size is standardised and roof sizes are adjusted to the size of the roof tiles. AM enables the production of free-form roof tiles. These free-form roof tiles can be used at any position and can, for example, accommodate parts of smaller chimneys. Ornamental roof tiles as seen in Japan can be produced with AM, too.

In the case of roof tiles, a smooth surface might be preferred to prevent pollution and to facilitate good water drainage. This surface can also be achieved by glazing. The characteristics are:

(1) Weather resistant
(2) Good glaze response
(3) Smooth surface

Free-form cladding (thin element)

Free-form cladding elements are used as a structure in front of a load-bearing structure. The thickness is reduced and the sizes are larger than those of bricks. To process large elements made out of silicate ceramic, it is important that internal stresses caused by shrinkage do not damage the part. The surface quality depends on the design.

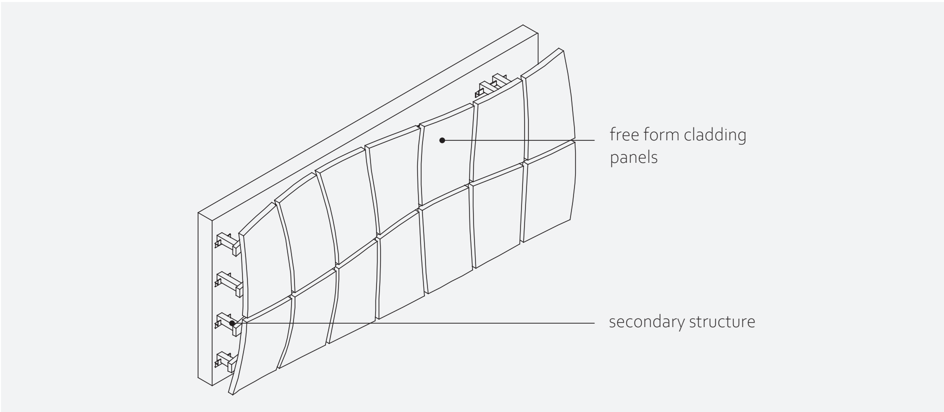

Figure 6.11 Free-form cladding

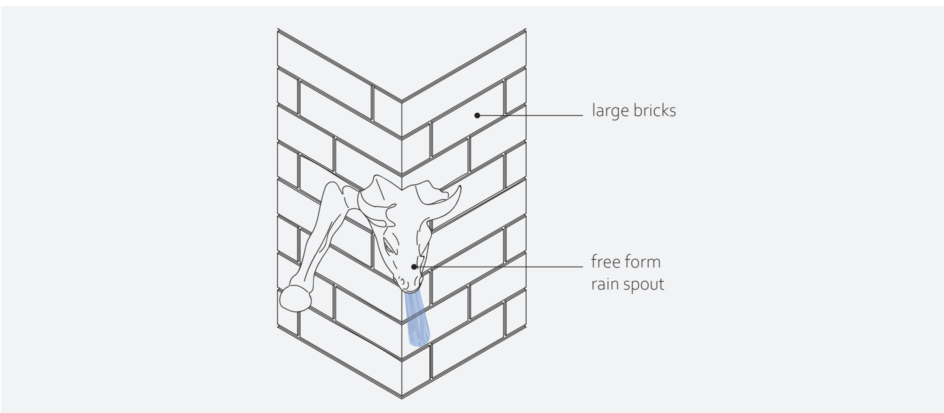

Figure 6.12 Rain spout

6.3.2 Bricks with added functions

Additively manufactured bricks with specific internal geometry to be used by birds are an example of bricks with added functions. These bricks are multifunctional and serve biodiversity. Older buildings have openings in their façades and under roofs where birds build their nests, while many newly build building do not. These bricks can either blend into the façade or can be designed as a visible ornament; and there are many more functional building parts that could be printed in clay.

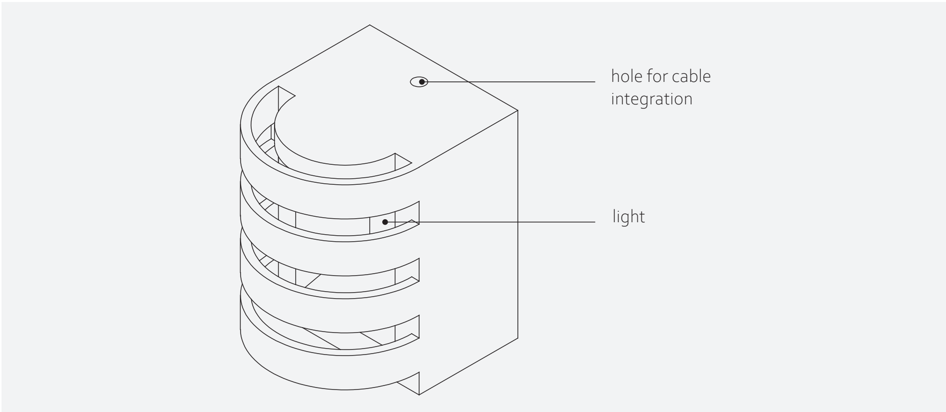

Figure 6.13 Accessory light

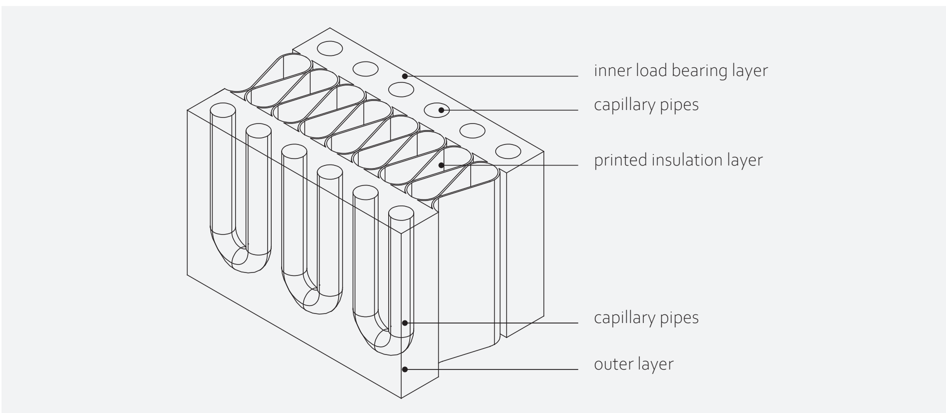

Figure 6.14 Heat exchanger

Rain spouts

Rain spouts are functional ornaments. They share the same characteristics as the ornaments. While they may be larger than normal bricks, their weight can be reduced with an optimised internal structure.

Heat collector

Printing tube structures in the internal geometry of bricks could facilitate their function as a heat collector by allowing water to be pumped through the brickwork. Since connections between the bricks need to be made, larger bricks are preferred.

The internal piping has to be watertight and therefore there should be room for glazing or the materials have to be fired at higher temperatures to allow for sintering. The surface quality of the piping has to be smooth to reduce resistance to the water flow.

6.3.3 Structural brickwork

Besides the aforementioned products, there are also clay building components that serve a load-bearing function. Such products are often substituted by (pre-tensioned) reinforced concrete, which limits design variants. Special attention must also be paid to the different characteristics of the materials; the thermal expansion of concrete and bricks, for example, do not match. Brickwork can get damage if these issues are not addressed appropriately.

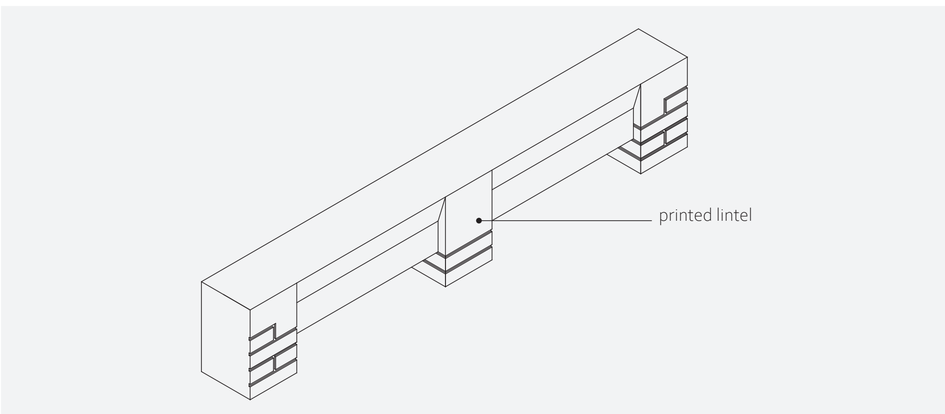

Figure 6.15 Lintel

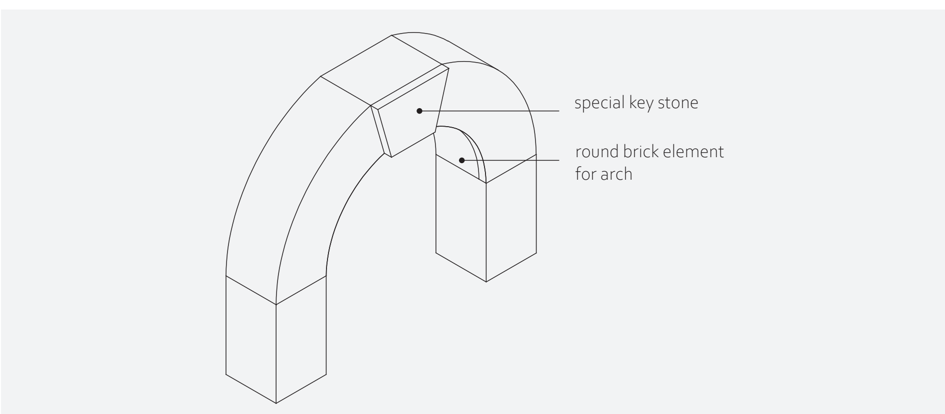

Figure 6.16 Arch and key stone

While prefabricated concrete building products are produced with formwork or adaptable formwork systems, the dimensions of the elements are limited and standardised. Therefore, ornamental additions are not a standard option, often added in a post-process production step and using additional materials.

Lintels

Lintels in masonry are used to carry the bricks above the windows. These large elements are load-bearing. The material quality and the density of the material to withstand the external forces are important. With AM, the internal geometry of a lintel can be optimised, for example by using multiple materials or a specific geometry to optimise material usage.

Density-optimised bricks

Density-optimised bricks could have an infill in which the amount of voids is controlled or they could have different material mixtures in one brick. A distinction of gradient materials can be made on concepts realised by process characteristics and those based on the use of two materials in one product (Hainz, P., Herrmann M. & Sobek, W., 2012, p. 8). Thermal bridges and the overall heat transfer can be reduced with an optimised printed internal geometry. Bricks with different characteristics regarding heat transfer in different locations inside the brick can be realised by changing the material and by producing bricks that consist of multiple materials. A gradient material can be printed if two materials are printed with a high resolution process.

Examples of the density-optimised bricks are those that use a geometrically controlled

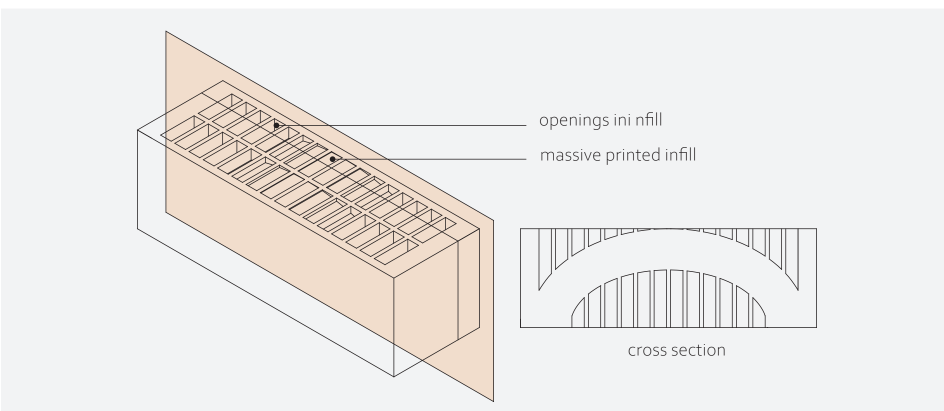

Figure 6.17 Print geometry-optimised beam element, e.g. a lintel

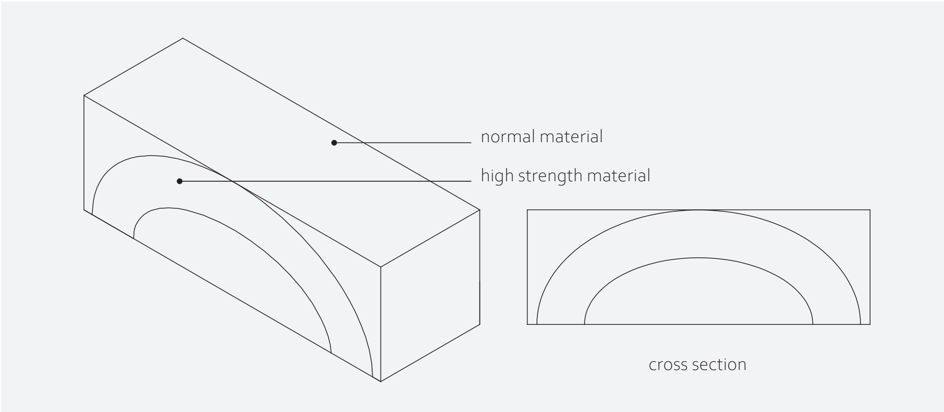

Figure 6.18 Density-optimised elements

infill or those that use multiple materials in one product. The resolution and surface quality will influence the steps in density changes within the brick.

Structural bricks with special inner geometries

Structural bricks can be optimised by the way bricks are used within the brickwork. Larger components are often massive and do not have an optimised inner geometry while traditional production processes cannot produce bricks that are hollow or consist of more than one material mixture. Structurally optimised brickwork uses AM in the same way as density-optimised brickwork. The bricks' weight can be reduced by printing material only where it is needed. If a massive brick is desired, the load-bearing performance can be optimised by printing with different material mixtures in one product.

The main characteristics of the bricks with a special inner geometry are the resolution of the print in order to apply the material where needed with an high accuracy. However, hollow bricks cannot contain a support structure of unbound print material. The surface quality depends on the preferred surface quality in the design.

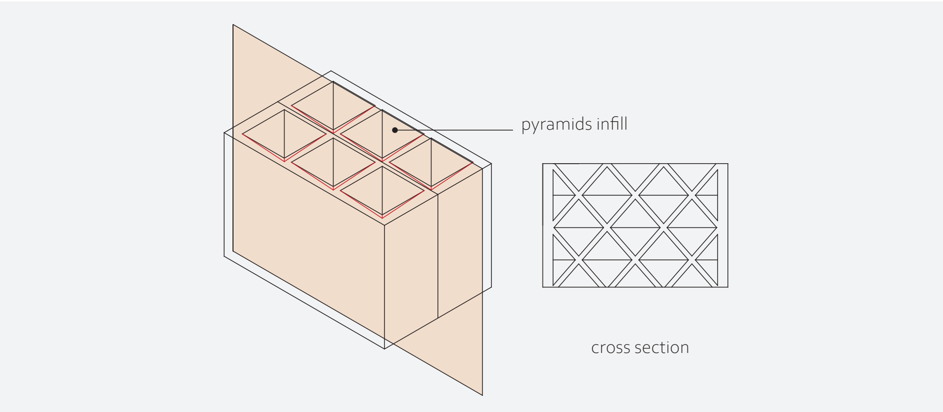

Figure 6.19 Structural brickwork with pyramid inner structure

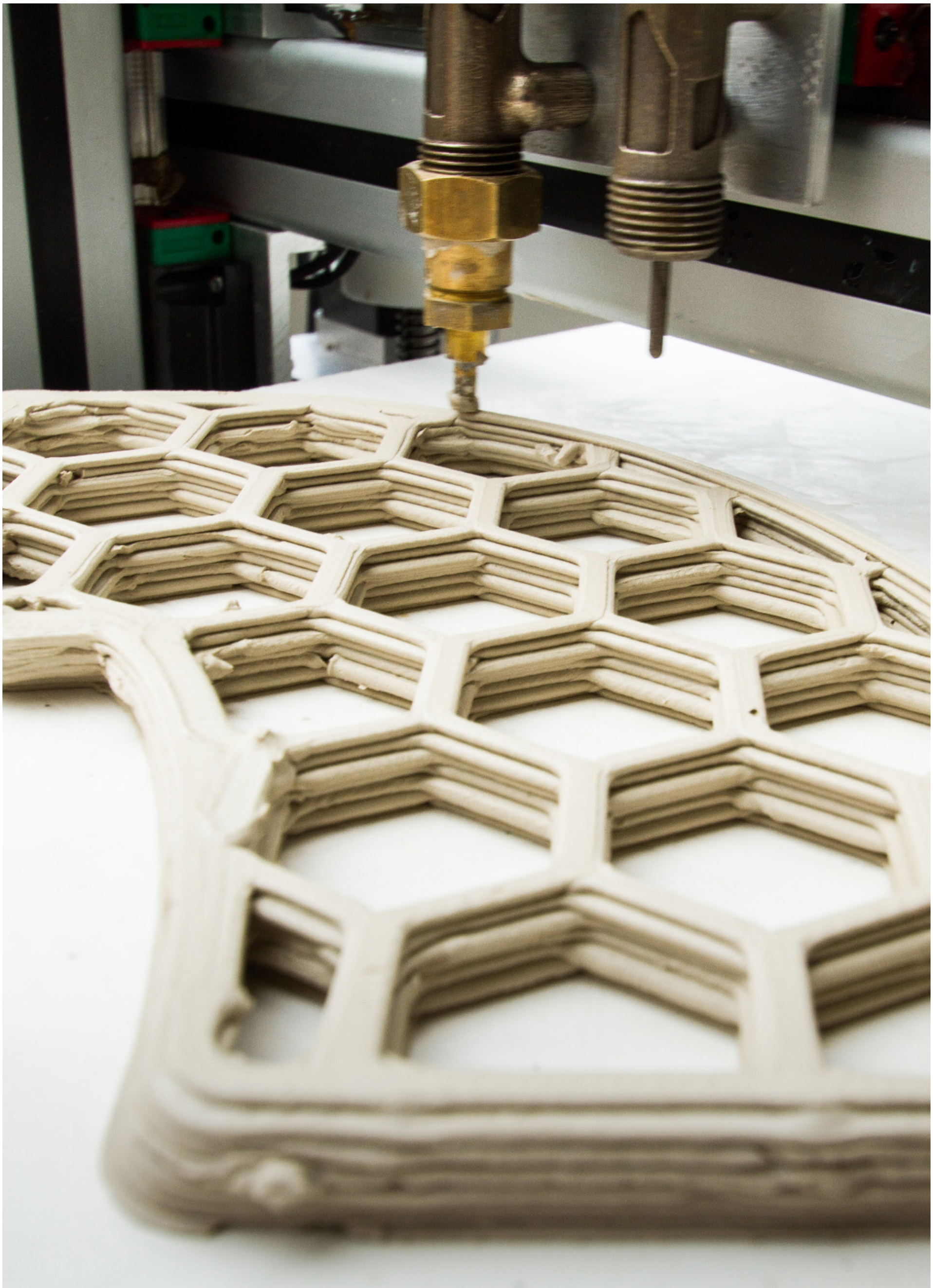

Figure 7.1 Principle of desktop robocasting
Image by M. Bilow

7 Definition of process demands

This chapter discusses the determining requirements to process clay with an AM process. The printing methodology and technology influence the type and affect the state of the raw material that can be used in the printer.

However, all components designed as examples in Chapter 6 have individual and different requirements. The focus of this chapter is to define the demands that need to be fulfilled to select a printing principle to print silicate ceramic (clay) for building components.

The requirements that need to be fulfilled regarding strength and optical appearance are the boundary conditions of the production process. The best matching AM methodology will be selected in Chapter 8 and further engineered according to the demands formulated in this chapter. The selection of a printing methodology is therefore not limited to the extrusion technology used in the preliminary stage of this research; all available AM categories are considered.

Next to the demands that are purely derived from the product's geometry and preferred properties, there are practical and economic aspects regarding the production process, too. Those practical and economic demands are, for example, related to the amount of material that can be printed at once. This aspect influences the choice for a technology that either works with material batches or with a continuous material feed.

7.1 Derived AM process demands

The defined and desired product properties can be divided into properties that are related to the production principle, the material, and they could have an economic motive.

The main demands are formulated and based on the proposed product design categories. The properties behind the production principle that influence the performance of the formulated demands are the parameters to which the production principles are compared and their applicability defined. The process properties all relate to the characteristics of the print process.

The properties of the material processed that directly influence the final process of one of the principles are:

(1) Material uniformity across batches
(2) Green stability
(3) Grain size/ plasticity

D. de Witte, *Clay Printing*, Mechanik, Werkstoffe und Konstruktion im Bauwesen 62, https://doi.org/10.1007/978-3-658-37161-6_7

The properties of the material processed that directly influence the product characteristics are:

(1) Shrinkage
(2) Material properties

To utilise a new production process, the requirements of both the process and the product need to be analysed. The building industry works with large parts. If those parts are additively manufactured, a large amount of material needs to be printed. Production time is an important factor. For every product there is an optimal balance between resolution and printing speed. Next to production time, replicability and homogeneity are important factors.

To guarantee the quality of the printed part, the homogeneity has to be regulated. Firing will change the molecular composition, but it will not compensate for material inhomogeneity. It is therefore important that the layers have the same homogeneity and that there is a good bond between the layers themselves. Inhomogeneity occurs due to the layered production technology. Printing processes with a lower resolution often have a ribbed surface. The cross-section of an additively manufactured part shows whether there are imperfections and how often they occur. To produce building components that will have the same characteristics, replicability assurance is mandatory. Process replicability is particularly important for the certification of load-bearing and structural parts.

99% pure materials are not uncommon for technical ceramics, but clay is a natural material. Therefore, there are fluctuations in the material composition. Especially with terra cotta, the material composition changes across different material batches. To process clay, the material composition needs to be monitored and the mixture needs to be tested before it is used. Although the material has to be tested before use, there will still always be a spread in the material composition, which means that the print technology has to be able to work flawlessly within a certain range of material compositions.

Building components that can be handled by hand can have a weight of approximately 23 kg. This is about 14 dm^3 or 24 x 24 x 24 cm. With openings in the printed geometry, the part will be larger. The size of the oven is not a determining factor but shrinkage during drying and firing can produce internal stresses. It is therefore difficult to make terra cotta objects larger than approximately 50 x 50 x 50 cm. Utilising AM of clay for the building industry means that larger parts have to be printed – 20 x 20 x 20 cm parts are not uncommon – but, depending on the material used, very large parts should not exceed 100 x 100 x 100 cm. For normal size parts, the print bed should have a dimension of at least 20 x 20 x 20 cm. Larger elements are not part of the scope of this research but they are discussed in relation to the scalability of the printing principles.

Besides the demands regarding the size and materials related to the processing technology, there are demands directly derived from the design.

Aesthetic design demands

Even though different designs have different surface qualities, accuracy and the control of the surface are important for all designs. There are designs that actually benefit from the characteristic surface of AM; the ribbed appearance cannot always be made with traditional technologies.

Support structures need to be removed before the element is fired. These structures are helpful when large cantilever elements are printed. To reduce weight and create watertight building components, it is favourable that support material can easily be removed from the internal voids.

Structural design demands

It is preferred that the printed parts have an almost homogeneous strength in XY and Z direction. If the layered application of material causes a certain anisotropic behaviour, this behaviour should be monitored to be able to predict it. The ability to print optimised structural components by use of different materials in a single part is also preferred.

7.2 Final materials properties

Materials need to be bound together. This can be done by direct sintering, adding a binder, and by applying a paste material in layers. Clay materials differ in their material composition, and thus there are different silicate ceramic materials.

Amongst these, earthenware and stoneware are relevant for the building industry. Higher grade materials can be used for outside cladding and water resistant building components which sinter during firing above 1100 degrees (like clinker bricks), while the more broadly available materials like terra cotta can be used for better internal insulation (higher R-value [$K{\cdot}m^2/W$)] / lower U-value [W/m^2K]) as well as for load-bearing functions if used in the form of larger elements.

For load-bearing and insulation applications, it is beneficial to use thicker, more porous elements, but for façade cladding the resistance against water absorption is a more important demand, which requires a higher grade of material with less porosity. The print direction may influence the strength, which is why good bonding is necessary. The main important criteria for a material used in an AM process are that they facilitate and fit in a printing process in which:

(1) Different densities can be printed
(2) Different porosities are used
(3) Different materials types can be printed

(4) Good bonding of the layers is realised
(5) Uniform material strength in all directions can be obtained
(6) The print technology sinters the product or allows it to be fired after it has been shaped in the printing process

7.3 Adequate application of material

The layers are applied on top of each other. The path and layer direction is influenced by the print methodology and manipulator. For slicing the parts, there is a distinction between 2D print paths and paths which describe a 3D line. The resolution and the accuracy is also determined by the movements and depositing of material by the manipulator and depositing mechanism. However, some designs have geometries where an adaptable print bed is beneficial. This could eliminate formwork, but the printing process should be able to print 3D paths instead of layers to benefit from e.g. adaptable formwork, when it is used as the building plate of the printer.

7.4 Processing large clay components

Although large clay components are not part of the scope of this research, an increase in size of the printed parts will occur when the production of additively manufactured clay parts is implemented in the building industry. Therefore, the scalability of the process is a factor that could become important in future. Since shrinkage of silicate ceramic components becomes more challenging with larger parts, water ratio and drying will become more important. It would benefit the AM technologies if the influence of shrinkage could be eliminated. Alternatively, dryer material mixtures or mixtures with larger aggregates could help to minimise shrinkage. The technology has to be able to process these material mixtures. Since larger parts for cladding are not the same size in all directions, the element will often be printed with a support underneath its largest surface. The print bed has to be adapted to these larger parts.

The most important requirements for producing large building parts are that the process scale can be increased, the material has less shrinkage, and that the print bed can be adjusted so that relatively thin elements can be printed with less support material.

7.5 Main process demands

Table 7.1 shows how AM technology and the material type influence the characteristics. The process demands derived from the designs that influence the performance most are:

(1) Accuracy
(2) Speed
(3) Ability to process a variety of material in one print
(4) Ability to print a free-form design
(5) Ability to print dense materials
(6) Surface quality

Although not every parameter is of the same importance for each additively manufactured clay part, the performance of the printing principles can be compared based on these parameters. A factor for the importance of the different parameters will be assigned. Post-processing steps could change the importance of certain parameters. This is taken into account with the factor of importance.

Table 7.1 Characteristics and derived conditions

	process property	derived process properties	material property	derived material properties	economical motive
strength	yes	uniformity of material depositioning	yes	uniformity of the mixture and ceramic type	price of material
surface quality	yes	how the layers of material are applied on each other	yes	material processability	price of material
need for post-processing	yes	printer accuracy	no		print speed
accuracy/replicability	yes	printer accuracy	(yes)	material uniformity over batches	price of material
material shrinkage during drying and firing	no		yes	material characteristics	
resolution	yes	how the layers of material are applied on each other	yes	minimum layer height caused by larger particles in the material, grain size or plasticity.	the print speed is a derived parameter of the resolution
weather durability	yes	uniformity of material application	yes	material characteristics	price of material
optical appearance	yes	printer accuracy	yes	material characteristics	price of material
insulation performance	(yes)	print accuracy	yes	material characteristics	
resistance against weather influences	yes	print uniformity	yes	material characteristics	price of material

The table shows characteristics and the relation to process and material properties. Economic motives and derived (and desired) material properties are indicated as well.

Continuation of **table 7.1**

	process property	derived process properties	material property	derived material properties	economical motive
material preparation	yes	pre print preparations	yes	material processability	time to prepare the material
freedom of design	yes	print principle	yes	material processability	the type of products that can be made
green strength	yes	print principle/curing	yes	material characteristics	
support material	yes	print principle	yes	matched material characteristics of material and support material	

The table shows characteristics and the relation to process and material properties. Economic motives and derived (and desired) material properties are indicated as well.

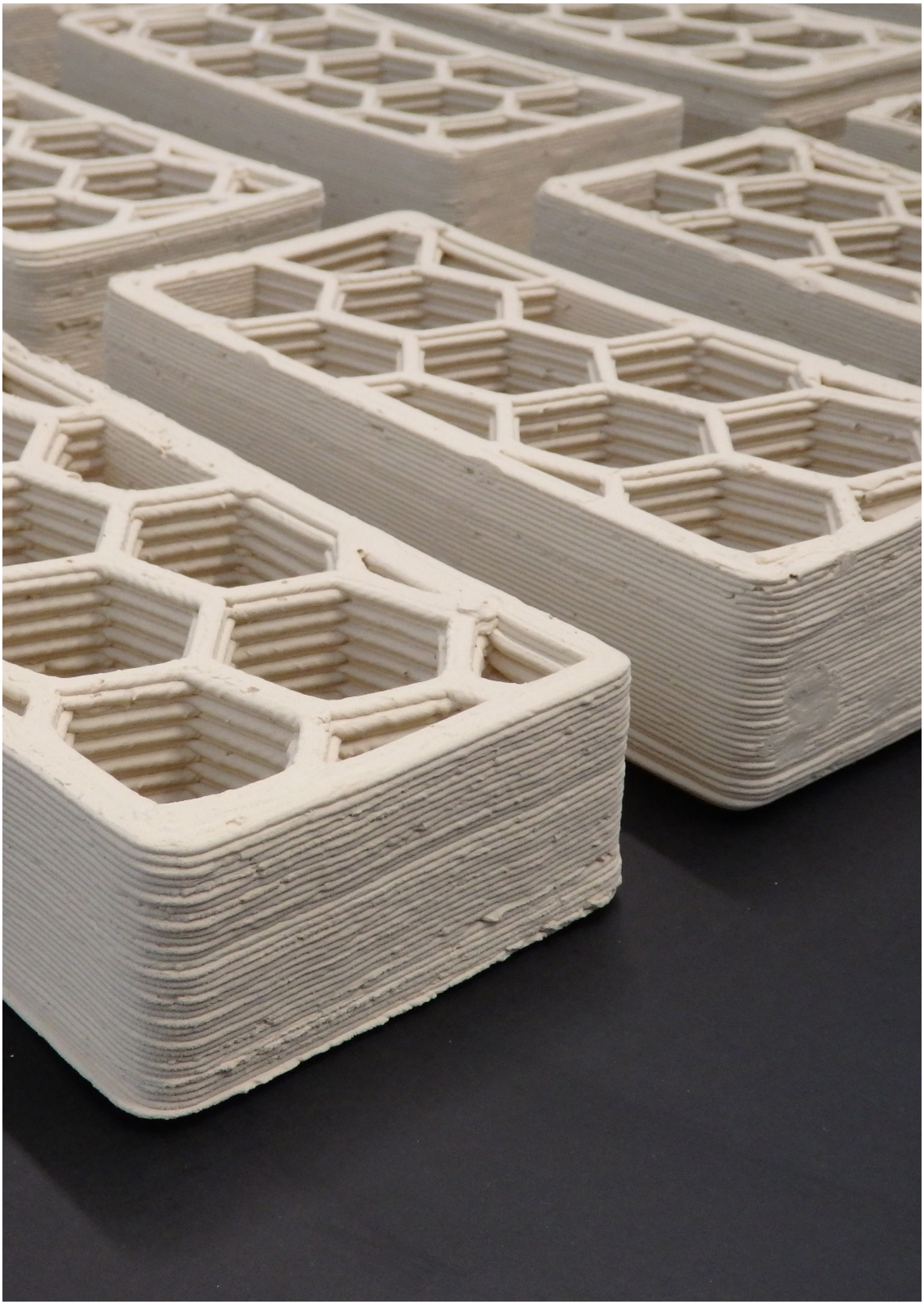

Figure 8.1 Additively manufactured bricks with honeycomb infill

8 Printing method

The seven different AM technologies, categorised according to the mechanism the layered materials are placed on top of each other, are described by ISO/ASTM standard 52900. The standard also categorises the different AM production methods available. Of these methods some can be used for ceramics. The main characteristics of the process influence the final geometry. These influences are:

(1) Accuracy
(2) Resolution
  - Can be post-processed but filigree or inner structure are difficult or impossible to post-process
(3) Support structure
  - Type of support (unbound material, selectively applied (different) materials)
  - Removal of support

Main differences for the processed material behaviour characteristics are:

(1) Raw material
  - Material mixture
  - Binder material
  - Compactness of the material / density

In this chapter, the demands that a new technology needs to fulfil are compared to the performance of the seven different AM methodologies.

8.1 Print files software demands

The printing process is controlled by use of special code that is converted into the manipulators movements. The 3D model is defined by the geometry and processed to define the position of the paths and areas that need to be printed, using a script, generated with, for example, a parametric design software package. Depending on additional requirements, the complete printing process can be controlled with additional scripting. The movement is translated into coordinates by a post-processor in a CADCAM software. The information can be elaborated with a sensor system that controls the process (Raspall, F., Amtsberg, F. & Peters, S. 2014, p. 334). The printer can thereby change parameters of

D. de Witte, *Clay Printing*, Mechanik, Werkstoffe und Konstruktion im Bauwesen 62, https://doi.org/10.1007/978-3-658-37161-6_8

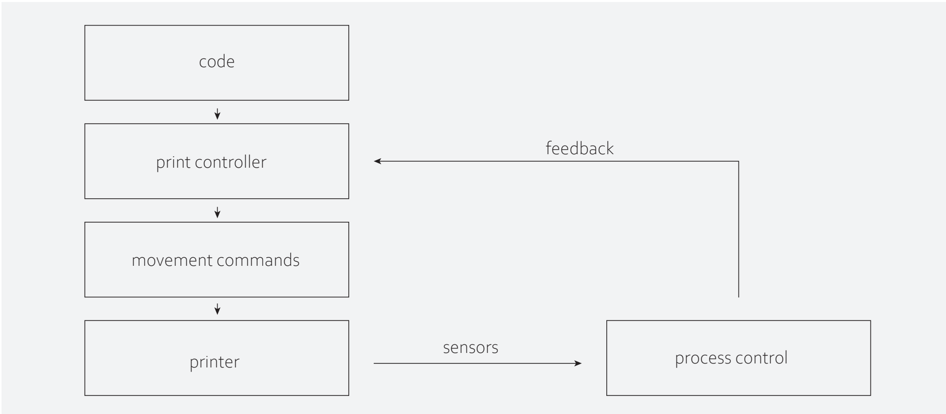

Figure 8.2 A set-up with sensors and a controller that monitors the process

the printing process in order to maintain a constant printing quality. Figure 8.2 shows a simple diagram of how a print controller and integrated sensors could function.

8.2 Quality of clay building parts

EN norms categorise building products according to their performance. For what type of application the clay products with the assigned performance class can be used in the built environment depends on local building regulations such as national building-codes and the EN 1991, for example.

Table 8.1 shows the categories of product performances indicated in standards to verify the demands corresponding with the categories in which the demands in local building regulations are defined. These characteristics are described in EN 771-1 (Table 2) (NEN-EN 771, pp. 27-28).

While all bricks can be categorised in a certain class using EN 771, there are some classifications that are influenced by a printing technology. Table 8.1 shows the relation of the categories addressed in EN 771 and the parameters that influence the performance of these categories.

These characteristics are mainly influenced by the material, the density of the material, and the accuracy and replicability of the material application in the printing process. The processing of different material types can improve the performance of the bricks. Some technologies cannot process all types of materials, causing a higher risk to produce products that are classified in a lower norm class and do not perform as desired.

Table 8.1 Categories of assessment in norms according to EN 771

assessment category	influenced by
type of unit	
dimensions and tolerances	printing process and material characteristics
freeze/thaw resistance category and its basis	material characteristics and layer bond
compressive strength	material characteristics and layer bond
configuration	
tolerances (range)	printing process
gross and net dry density and tolerances	printing process
water absorption	material characteristics and layer bond
initial rate of water absorption	material characteristics and layer bond
thermal properties	material characteristics and layer bond
category of active soluble salts	material property
moisture movement and its basis	material characteristics and layer bond
reaction to fire	material characteristics and layer bond
water vapour permeability	material characteristics and layer bond
bond strength	material characteristics and layer bond of the product within the brickwork bond
dangerous substances	material property

categories as in en 771 (nen, 2015a)

8.3 Process methodology for AM of silicate ceramics

The seven AM methodologies that will be compared to the demands are:

(1) Binder jetting
(2) Directed energy deposition
(3) Material extrusion
(4) Material jetting
(5) Powder bed fusion
(6) Sheet lamination
(7) Vat photopolymerisation

Experiments are performed with four technologies for AM of clay as mentioned in Chapter 5: Powder bed fusion, binder jetting, vat photopolymerisation, and extrusion-based technologies. All of them have advantageous and disadvantageous properties depending on the size of the building and the achievable density of the components. The defined conditions are not considered equally important since there are basic conditions that become less important if parts can be post-processed. The surface quality, for example, can be improved easily and therefore this condition is of less importance for selecting a print technology. In contrast, there are conditions related to the uniformity of the material that cannot be improved by post-processing. Liquid methods such as stereolithography are photopolymer-based and need a material container with fluid the size of the component. The polymer needs to be removed later to be infiltrated, or is burned away during firing, leaving small voids. It is causally related to the technology and cannot be compensated for. The impact of the important material uniformity parameter becomes clear for the individual printing methodologies.

The parameters related to the print principle are listed in Table 8.2 with an assigned value to these characteristics. Since there are many printing technologies, the important methodologies on which they are based are used to select a AM methodology. A score from 1 to 5 is used to indicate their performance. Six parameters are assessed to compare the different AM methodologies. The parameters defined are based on the design examples' characteristics and the defined assessment categories of the standards:

(1) Accuracy
(2) Speed
(3) Ability to process a variety of material (different batches)
(4) Ability to print a free form design
(5) Ability to print dense materials
(6) Surface quality

Table 8.2 Characteristics and derived conditions

parameter	influence	percentage
accuracy	The accuracy of the printer involves the replicability and process control of the 3D print.	15
speed	The speed influences the amount of products and the size of products that can be made.	20
processability of a variety of materials. different batches	Not all processes are able to process a variety of materials. However, there is a wide variety of clays. These clays can be used for different products. The ability to process a variety of materials with the same printing process is therefore desired.	20
ability to print a free-form design	The ability to print forms that cannot be made by other technologies is the benefit of the process. While all printing principles are designed with this in mind, it is less important than other parameters.	15
ability to print dense materials	The density of the material relates to the strength of the material. Since the printed parts will eventually be used in the built environment, strength is important. Therefore, a compact and dense print is desired. Optimisation can take place by removing material from the inner geometry where possible.	20
surface quality	The surface quality is determined by the process and the resolution. Since the surface quality influences the amount of post-processing required, it is a characteristic that has to be considered in the comparison of the applicability of a production principle.	10

Since the file handling does not change the quality of the manufactured parts, the parameter regarding file types is neglected in the comparison. The doughnut charts based on Table 8.3 show the influence of the weight of the process conditions on the overall performance of the process.

Table 8.3 Process performance for clay ceramics

	accuracy	speed	ability to process a variety of materials	ability to print free form designs	ability to print dense materials	surface quality	needs post-processing
weight	15	20	20	15	20	10	
binder jetting	++++	+++	++	++++	++	++++	cleaning and infiltration
direct energy deposition	++++	++++	+++	+++	++++	+++	removal of support structures
material extrusion	+++	+++++	+++++	+++	+++++	++	removal of support structures
material jetting	++++	++++	+	++++	+++	++++	removal of support structures
powder bed fusion	++++	+++	++	++++	++	++++	cleaning and infiltration
sheet lamination	+++	++++	+++	++	+++	++	cleaning
vat photo- polymerisation	+++++	++	++	+++++	+++++	+++++	removal of support structures

Continuation of **table 8.3**

	printed clay with this technology already	support material available (for clay)	in surface resolution nozzle size	print bed size	speed	limitations	additional process characteristics
binder jetting	yes	yes (yes)	high, medium, low	small, medium, large	low	closed hollow objects cannot be printed	the material must be conditioned
direct energy deposition	no	yes in same material (no)	high	small, medium, large	low		the material must be conditioned
material extrusion	yes	yes (no, apart from same material)	high, medium, low	small, medium, large	medium, high		the typical ribbles
material jetting	no	yes (no)	high, medium, low	small, medium, large	low		
powder bed fusion	yes	yes (yes)	high	small, medium, large	low	closed hollow objects cannot be printed	the material must be conditioned
sheet lamination	no	no (no)	high	small, medium, large	medium		the layer connection is a different material
vat photo- polymerisation	yes	yes, same material (yes)	high, medium	small, medium	low		material mixture has to be UV curable

Figure 8.3 Performance of binder jetting

Binder jetting

The results of printing silicate ceramic with the binder jetting technology show that the accuracy is high, but completely closed internal voids cannot be printed using this methodology. With binder jetting, the layer height is adjustable, but cannot be increased significantly without major changes to the printer set-up. The density of the material depends on the ability of the material to be compacted on the print bed and the amount of binder agent used.

Figure 8.4 Performance of direct energy deposition

Direct energy deposition

Direct energy deposition fuses material together by melting the material before it is applied at the desired location during the printing process. However, the ceramic material has to be melted to be processed by a direct energy deposition or it has to be mixed with a material that acts as a binder agent. This binder agent should have a lower melting temperature. The binder agent reduces the density of the print. However, if a silicate ceramic can be processed with this methodology, the freedom of form is high and internal, fully closed voids could be printed.

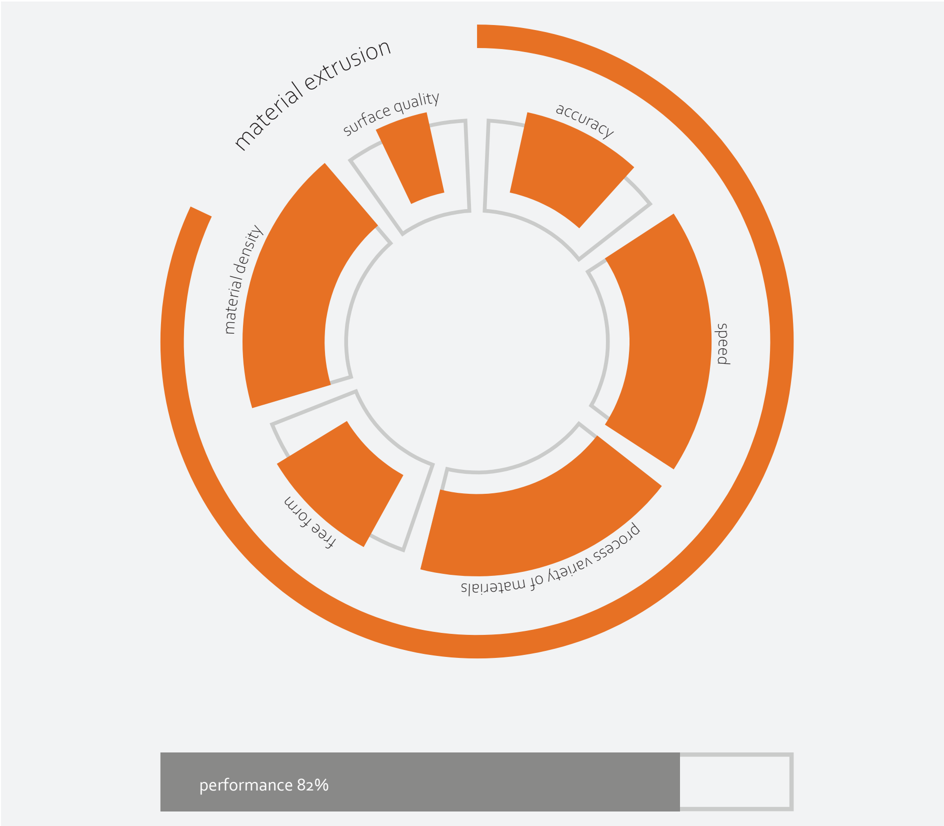

Figure 8.5 Performance of material extrusion

Material extrusion

Material extrusion has already been used to process silicate ceramic mixtures. The material is a pasteous material and is placed on top of each other in layers. The resolution can be adjusted to the needs of the print, and by changing the nozzle of the printer very filigree but also thicker paths of material can be extruded. This allows this methodology to process a higher amount of material than other processes. The surface quality can be easily improved by post-processing while a relative stable green body can be printed, which, theoretically, does not have a porous inner structure. The accuracy is mainly determined by the nozzle diameter, the control of the extrusion flow, and the manipulator the print nozzle is attached to.

Figure 8.6 Performance of material jetting

Material jetting

Material jetting sprays the material through the print head at the desired location during the printing process. However, the ceramic material has to be mixed to become liquid, free-form geometries can be printed on a flat print bed. Internal, fully closed voids can be realised, but post-processing is needed to sinter the ceramic parts together after the print is completed.

Figure 8.7 Performance of powder bed fusion

Powder bed fusion

Powder bed fusion relies on sintering a binder agent around the silicate ceramic parts on an underlying layer of material. The material is locally heated, melted, and sintered together. The finished product needs to be post-processed. Due to the limited strength of the heat source, the layer height is limited, which could reduce the printing speed compared to other technologies. Since the part is printed in a powder bed system, all internal voids are filled with material. Fully enclosed voids cannot be realised, which reduces the freedom of form. The printed model needs to be post-processed to remove the binder agent and to sinter the ceramic together.

Figure 8.8 Performance of sheet lamination

Sheet lamination

This method generates a 3D model by laminating cut parts of a sheet together. The materials used are glued together and may need to be sintered after the model has been printed. Since a matrix is needed to keep the silicate ceramic in the sheet material, the thickness is determined by the resolution in the Z direction. The resolution in XY direction differs and is defined by the accuracy of cutting the sheet. The speed can be relatively high, but because there is a difference in resolution in XY and Z direction, the surface quality is expected to be slightly lower than with other technologies that rely on a binder agent.

Figure 8.9 Performance of vat photopolymerisation

Vat photopolymerisation

Here, a photochemical reaction initiates a cross-link reaction in a polymer. To print a silicate ceramic, the material is dissolved in the polymer. While the polymer is a liquid and photopolymerisation often has an upside-down building platform, high resolution prints can be realised; however, support structures are often needed. The density of the printed materials can be high, but this means that, during post-processing, the prints need to be infiltrated with ceramic material before they are fired. The print speed is relatively low due to the high resolution and (limited) strength of the laser, which determines the layer height.

8.4 Post-processing

Due to the relatively large size of the designs, a relatively fast printing method is desired, but the printer should be able to realise all design ideas.
The speed of a powder bed-based method seems to be inadequate to generate a larger quantity of large building parts. An extrusion principle such as robocasting has the advantage that the speed can be increased by the section of the extrusion. The resolution of this technology can therefore be adapted easily, and with some post-processing the desired surface quality can be achieved. A combination of additive and subtractive manufacturing before firing can be a solution to increase the quality of the extruded ceramics to compete with the higher resolution of additively manufactured parts using 3DP. A solution could be a hybrid approach: Print – (Dry - Mill – Print) - Dry - Fire - Mill - Fire - Glaze).

Green machining, a machining process that takes place before the product has been sintered, has the additional advantage of saving 90% time and 95% of tooling costs (Carter & Norton, 2013, p. 431), since curing by glassification does not take place before firing. For steel, there is a comparable production process, whereby material is welded on top of each other, and the product is then milled to obtain the desired geometry accurately.

8.5 Robocasting technology

The Lutum printer, based on automated 3D material extrusion robocasting, was used to produce (advanced) clay-based ceramic building components in the preliminary stage of this research. The advantage of extrusion is the higher density of the printed product without having to infiltrate the green bodies after shaping; however, compared to some other technologies, the resolution is lower.
Extrusion meets the most important conditions of AM in the building industry. The important factors are the ability to process a variety of materials in a pasteous mixture to guarantee compactness. In addition to the ability to process a wide variety of materials, the less limited printing bed also facilitates future changes in material and the size of the printed components, especially with regards to large building parts in the future. Even though the resolution is lower, the speed is higher and the surface quality can be improved by post-processing. The largest challenge is to match a support material that could be printed. Due to the shrinkage of the clay after printing, internal stresses can occur. Although it is convenient to have a support material that is lost during firing, a support made of clay itself is a solution, too. This kind of support material can be removed by post-processing, before or after firing. The usage of the same material as support material is common with other AM methodologies, as well.
Thus, based on the criteria, material extrusion is the best matching technology with its ability to post-process and to work with a semi-open print code for producing larger clay

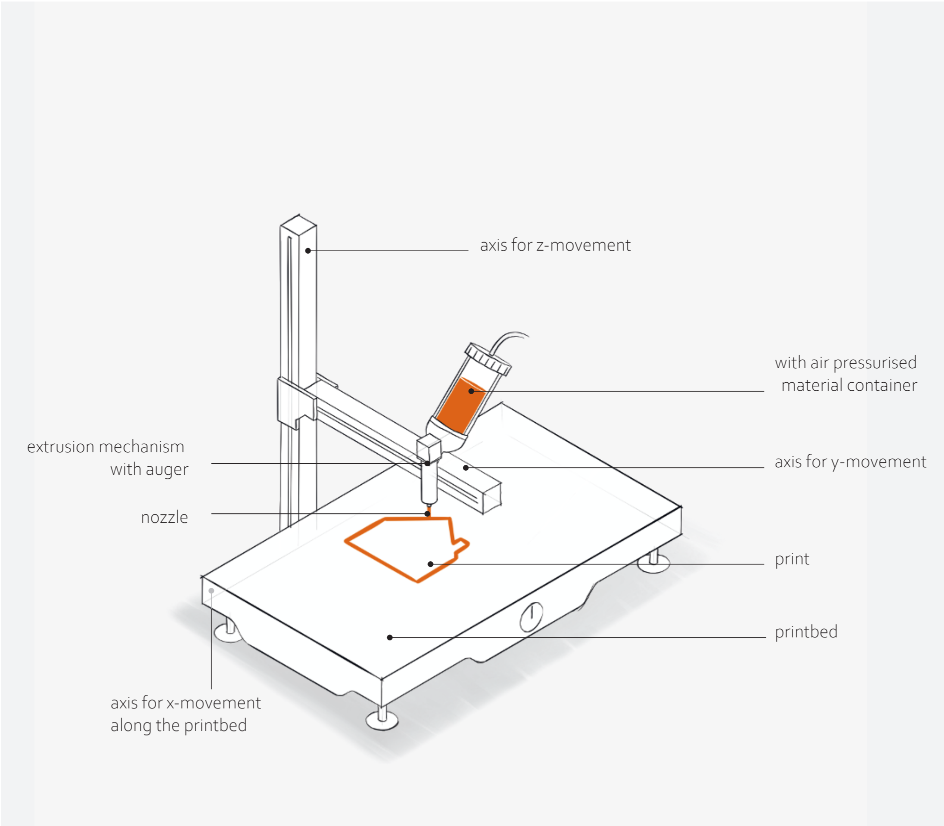

Figure 8.10 Desktop robocasting printer for clay

building components.

As mentioned before, norms define the performance of the clay products. Robocasting does not seem to pose any limitations on producing bricks that are in line with these norms. However, testing needs to be carried out to verify whether the products comply with e.g. EN 771-1.

Figure 9.1 Dried clay
Shrinkage of natural clays causes cracking

9 Printing material

The type of material mixture used was not the starting point of the development of the AM process; however, the processable type of ceramics is an important factor because the material has a significant influence on the final material properties of the printed part. The material is usually optimised for a production processes. The processes within silicate ceramic (clay) processing are engineered such that a broad spectrum of different mixtures can be used. The different processes will, therefore, use different materials but they are all based on the same material typology.

The selected AM process category is based on the extrusion principle. Robocasting as AM technology has to be adapted to process the silicate ceramic materials, and available material mixtures have to be adapted so that they can be processed with robocasting.

As a start, known materials were adjusted for AM. Among these materials was Creaton 208 from Georg and Schneider. The material was used in the preliminary research stage with the desktop robocasting machine. The first tests showed that it could be extruded well with the printer described in §5.5.1. The material was composed of a dried material mixture which contained the ceramics and chamotte. Water and a plasticizer were added to prepare the mixture.

The material was evacuated to prevent air pockets in the printed part. The fine, broken ceramic parts – chamotte – in the mixture provided adequate stability to print multiple layers without the use of additional support material.

9.1 Material for robocasting

The material types that can be processed with the different printing principles differ because of their viscosity. Viscous material mixtures were used during the preliminary research stage for additive manufacturing of ceramics by use of the desktop robocasting printer. These robocasting-extruded clays have a higher plasticity than the clays used with extrusion processes for vertical perforated clay blocks, for example.

It is essential how the material is prepared and what materials can be used for AM. For AM, the viscosity of the material and a low shrinkage is important to facilitate accuracy. The plasticity can be measured by use of the Pfefferkorn test (Figure 9.2). With this method, the plasticity of different material batches and clay mixtures can be tested and compared to each other. (Pfefferkorn (1924) in Andrade, F.A., Al-Qureshi, H.A. & Hotza, D. 2011; van der Velden, J.H., 1979 p. 533). The shrinkage has to be measured by preparing samples that are dried and fired.

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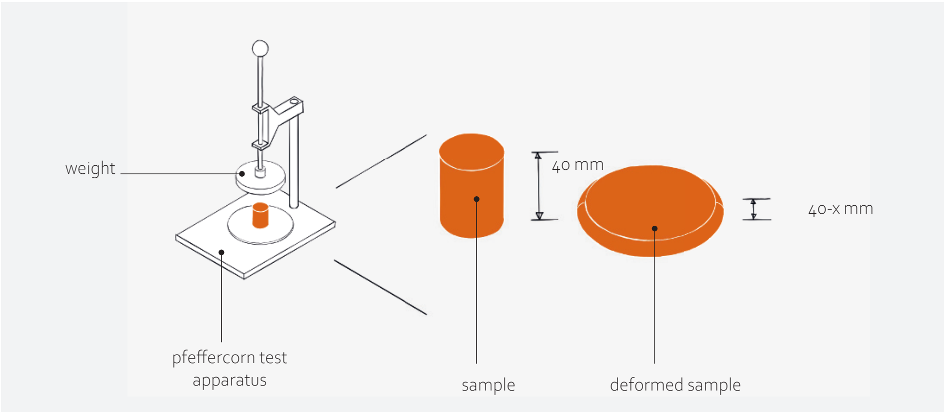

Figure 9.2 Pfefferkorn test apparatus

Because the selected printing principle is based on the same extrusion principle as the printing principle used during the preliminary research, experimental results obtained of these prints can be used to define a material and to improve the technology. In the preliminary phase of the research, flaws in the material processed were visible. The main challenges with the printer based on the extrusion principle are shown in Table 9.1, which highlights these flaws and addresses the cause and possible solutions.

Table 9.1 Known possible flaws and the influence of the material

flaws	proposed solution
air inclusion in the system	de-air the material before it is processed in the printer
plasticity regarding stability of the print	improve material's green strength while maintaining or decreasing the viscosity
plasticity regarding the extrudability of the material	improve the material's plasticity
accuracy of the print	increase material's stability
replicability of the print	reduce material fluctuations
asymmetric drying	reduce the water ratio in the material

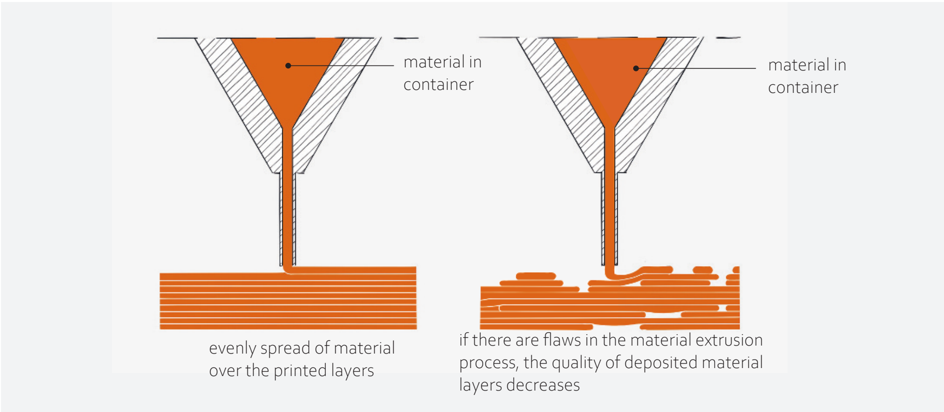

Figure 9.3 Flaws in extrusion

9.2 Clay composition

The ceramic mixtures contain:

(1) Ceramic
(2) Chamotte (increases green strength and reduces shrinkage)
(3) Quartz (sand)
(4) Water
(5) Additives e.g. liquefier

The amount and type of ingredients determine the final material properties. To extrude the ceramic, the material has to be preprocessed to make it fine enough to flow through the nozzle. Air needs to be removed to prevent the printed material becoming insufficiently compact. Additives are used to improve the plasticity of the mixture; soda is often used for this purpose. Improved plasticity makes the material better processable (Figure 9.3). After firing, the influence of the additive can be neglected on the products performance.

9.3 Clay preparation for AM

The challenge of shrinkage due to the higher amount of water needed for stronger and more water resistant ceramics is also tackled by use of plasticisers.

To examine the material characteristics before firing, a DTA (differential thermal analysis) is carried out. This analysis shows the specimens' temperature in comparison to reference material to see if there is an endothermic or exothermic reaction that would indicate a phase change. In case of water evaporation, an endothermic reaction is seen in the plotted graph. With ceramic materials, quartz inversion can also be identified. The temperature curve to fire the green bodies is influenced by the mixture, as well. Higher kaolinite means more chemically bound water, which causes a weight reduction at around 400 degrees centigrade. The presence of graphite becomes visible at 180 degrees centigrade because of the strong bonding due to van der Waals forces between graphite and free water, causing the water to evaporate at a higher temperature than its boiling point. Lower quality ceramics will be more porous, but will also be fired at a lower temperature. There will be some sintering between the particles but no vitrification as can be achieved with stoneware materials at 1200+ degrees centigrade.

The temperature curves are important for firing. A lot of chemically bound water ask for a slower firing process up to 400 degrees centigrade. Longer firing times directly influence production times and costs, and this influences the selected material for building components, too.

According to the empirical prints and preliminary research, the material processed in the printer must be prepared to a homogeneous mixture. The material should be evacuated to prevent air in the extrusion system (Travitzky, N., et al. 2014, p. 738), which causes interruptions in the material lines extruded. The reduction of air in the material by evacuating also decreases the viscosity, making it easier to extrude the material due to the better plasticity (Roos, W., 2019).

The material for the tests has been mixed by an universal double arm mixing and kneading machine, where after the material is de-aired in a de-airing extruder. The extruded material could then be processed in the 3D printer. However, these are only the steps to prepare the clay mixture; to have a workable mixture, the amount of water must also be controlled. The composition of the clay mixture is influenced by the amount of water and to obtain the desired plasticity the mixture needs to rest. The use of liquefier in the mixture can increase plasticity, too, but the effectiveness is highly dependent on the dosage and the time the mixture has to rest and to “mature”.

The material mixture processed with the desktop printer had a relatively high water content – up to 35% for certain material mixtures (Cruz, P.J.S., Knaack, U., Figueiredo, B. & de Witte, D., 2017, pp. 3-4). The dosing and relative purity of the materials must be controlled to replicate the material mixture. Therefore, DTA curves can provide information regarding the material composition, even though it is not a method to determine the exact composition. In addition to controlling the material mixing and the DTA curve, a Pfefferkorn test has to be carried out. This is a simple, widely used test to examine the clay’s plasticity; it works by deforming a specimen by impacting it with a round disc from the top.

9.4 Materials for multi-material printing

If two different materials are printed in the same design, the materials should share some basic characteristics, especially those that relate to shrinkage. The shrinkage of the printed parts needs to be controlled and it is preferred that the overall shrinkage is reduced. Therefore, if printing with multiple materials, the behaviour of the different materials regarding shrinkage during drying and firing has to be adjusted to each other. If there is a difference in shrinkage, internal stresses will cause the printed parts to be damaged by the internal forces. Permissible differences in the material could be the colour and the type of ingredients to obtain a more porous material.

9.5 Recycling

Recycling extrusion-based silicate ceramic products or waste is easy. The material that comes off the shaped body during post-processing can be recycled, and material that has been fired can be recycled, as well. Although the material may be clumped together, the same mixture can be recreated by adding water, unless the material is mechanically broken by grinding. If it is ground, the size of the chamottes might be reduced, increasing the overall surface area of the particles, which could make the material dryer. Thus, to obtain the same plasticity more water content is needed, but the green strength could be less because the finer material interlocks less. Also, shrinkage increases since there are less coarse bodies that hinder shrinkage. Material that has been fired can be used as chamotte in new material mixtures. To do so, it has to be ground and sieved.

With powder bed AM technologies, only the unbound material is recycled. Whether the materials are sintered together or bound by use of a binding agent, these materials are harder to recycle.

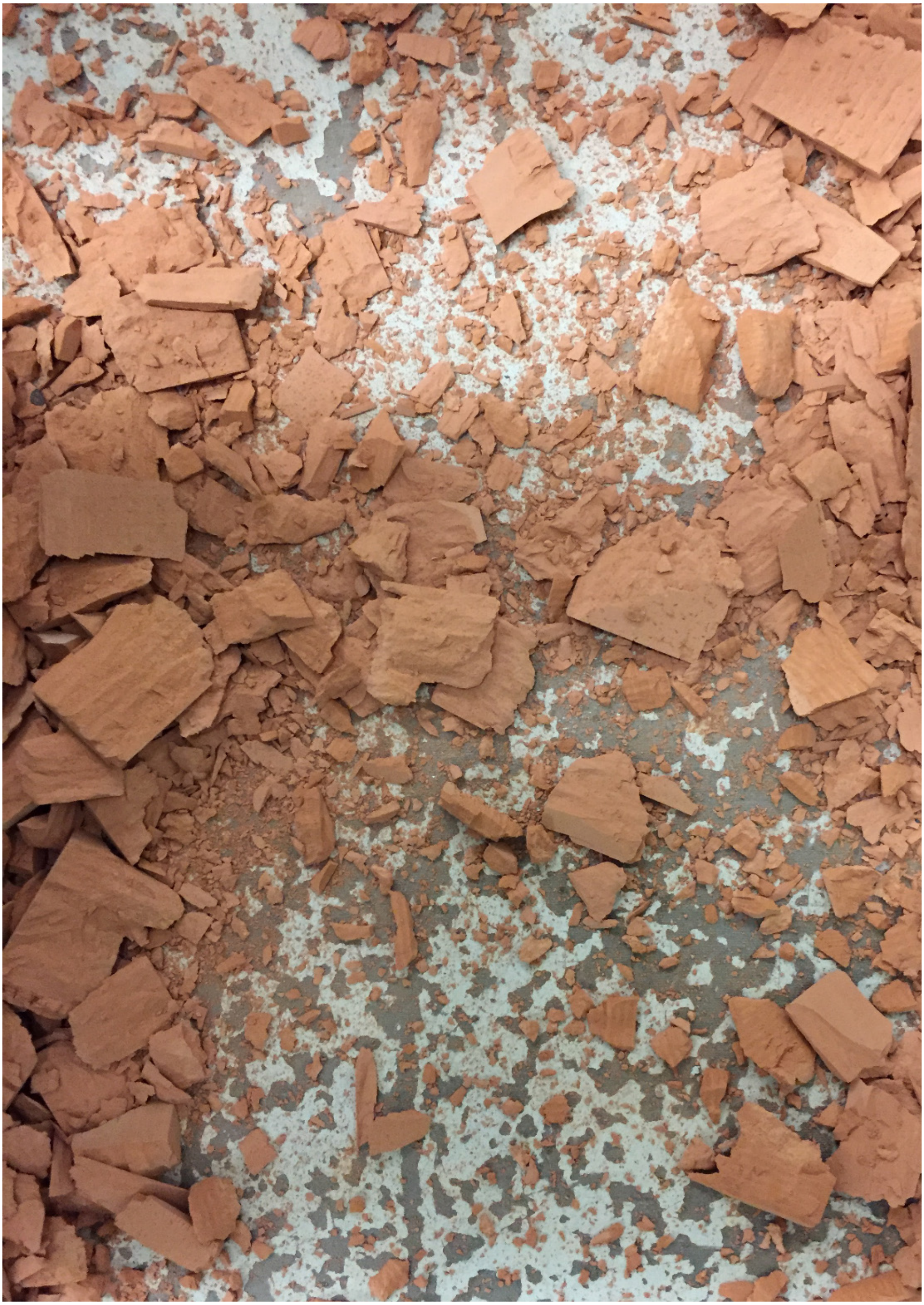

Figure 10.1 Shards

10 Performance of the first additive manufactured samples

In Chapter 6, the design study showed ceramic products that benefit from an AM technology. These products cannot be made with other technologies or there is an economic advantage to print them because the method does not require formwork, for example.

The printing method was chosen according to the desired performance and based on the conditions defined in Chapters 6 and 7. During the design of the new printing technology based on extrusion, tests with the desktop printer continued. This chapter discusses the performance of the first AM parts printed with the desktop printing technology adopted to silicate ceramics (clay) from the preliminary research.

A key question is how the influence of the AM production technology on ceramic building components can be examined. Due to the characteristic layered production method, the influence must be examined before products can be used in the built environment. Samples are tested for this purpose. Brickwork and other ceramic building components are described in international standards and national appendices. Several standards address the compressive strength but not the tensile strength. Technical ceramics, however, are described in standards that address both, compression and tensile tests.

While there are no applicable standards for ceramic building components made with AM, the performance of these parts is described in this chapter. The tests are divided into aesthetic and structural performance. The aesthetic performance is influenced by how accurate the geometry can be produced with the chosen material. Parameters that influence the quality are:

(1) The replicability
(2) The print resolution
(3) The variety of material that can be processed using the print technology
(4) The possibility of multi-material printing
(5) The achievable amount of free-form
(6) The post-processing methods used

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Figure 10.2 Visible defects in a printed brick
The defects are caused due to a material shortage

Figure 10.3 Visible defects in a printed brick
The defects are caused due to a material shortage causing an interrupted infill. The roughness of the infill caused that the material started sticking on the nozzle causing this top layer pattern.

The structural performance is determined by:

(1) The replicability
(2) The cohesion of the individual layers in horizontal and vertical direction
(3) The layer orientation and print direction
(4) The material usage
(5) In case of multi-material, the cohesion of the different mixtures

Other performance factors relate to costs related to machine investment and the eventual print speed. Tests are performed on the compressive strength and tensile strength. The first tests performed were carried out to understand the material behaviour. Results of samples printed and tested by master students were used for the same purpose. Uncertainties were observed in these test results. Some results seemed to be categorised in the wrong test direction, for example. Due to sanding, the outer surface didn't show the print direction anymore. Questionable results were therefore rejected.

To determine the aesthetic performance, the requirements defined in Chapter 6 are used to assess the first 3D printed parts.

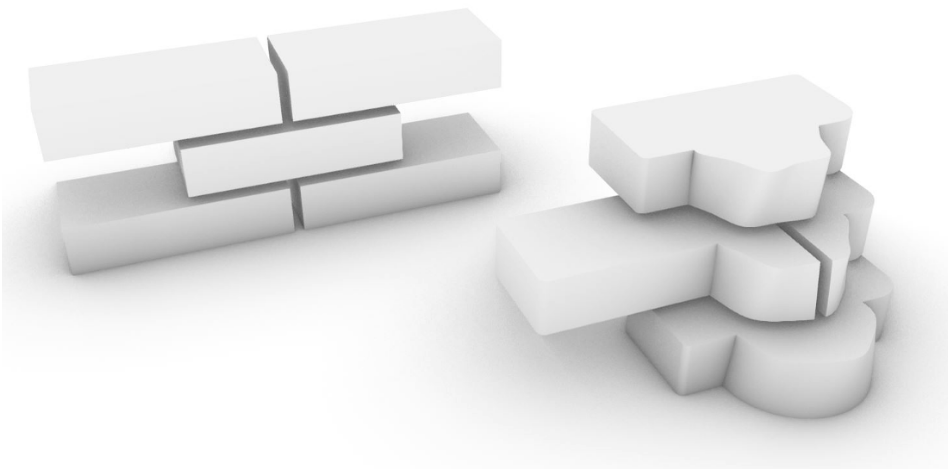


Figure 10.4 Design corner bricks in CAD

Figure 10.5 Printed corner bricks

Figure 10.6 Internal defects in a printed brick
The internal defects caused internal stresses and formed cracks during firing.

10.1 Aesthetic performance

As mentioned, the most important parameter for this assessment is replicability. The requirements regarding the design defined in Chapter 6 are used to compare the printed parts. Since additional engineering time needed during the development of the printing process caused fewer test samples to be printed than anticipated, some characteristics could not be compared to the demands. Therefore, the produced bricks are examined on the condition whether designs could be printed. The first printed bricks showed that a certain degree of design freedom and a certain amount of cantilever could be printed. Defects were observed, exemplified in Figures 10.2 and 10.3.

During the development of the new printer, tests were performed on the desktop printer printing corner bricks. Figures 10.4 and 10.5 show printed corner bricks in brickwork. The design consisted of multiple bricks at the corner of an imaginary brickwork wall. The circle at the bottom gradually changes into a star shaped form. The contour of the star shape becomes visible in the top right brick. Inside the bricks is a honeycomb infill. The infill was selected to reduce the printing time, but also to avoid internal stresses. The geometry represented the 3D model and the layers were printed well. Figure 10.6 shows a section of a brick printed with 100% infill. Due to internal defects, internal stresses caused the brick to de-laminate during firing.

Another type of infill was printed to investigate if cantilevers can be printed and to experiment with infill geometries. Figures 10.7 and 10.8 show an infill structure composed of pyramids. The print is a result of the design study in Chapter 6. The pyramid

Figure 10.7 Top view of a sample of a pyramid infill
Sample printed by M. Fischer

Figure 10.8 Side view of a sample of a pyramid infill
Sample printed by M. Fischer

geometry is a stable infill which consists of closed voids. In the print, small opening due to shrinkage are visible, but fully closed voids can be realised, which is not possible with every printing technology. Since robocasting does not use a powder bed and offers the printing of small cantilevers, internal voids can be realised. Straight lines of material were extruded to print this geometry. The distance between the individual lines changes every layer, but each layer looks like a grid. While the red material used for this experiment was harder to print, the shown sample consists of multiple prints that are joined with a mortar.

The performance of the first printed products is satisfying, although improvements are needed to utilise the robocasting technology on a larger scale. Therefore, the performance of the before mentioned parameters need to be improved and the capabilities of the technology need to be guaranteed.

10.2 Structural performance

To test the strength of the AM parts, specimen are printed and tested to obtain a general understanding of the failure mechanism.

The samples were tested in a common universal testing machine. Advanced ceramics are often tested with flat or round tensile specimen with a gage between the two shoulders (ASTM, 2018). Since these are hard to produce due to the brittleness of the non-technical ceramics, the three-point bending flexural test was performed with samples that can be printed with the printer and material. The cubic samples for compression are tested in different directions to obtain information on the connection between the individual layers. The tests take place at 90 degrees, 0 degrees, 90 degrees changing XY direction every layer and 0 degrees changing XY direction every layer. Three-point bending tests of AM beams are carried out to obtain information on tensile strength.

Figure 10.9 shows different types of samples for the compression tests, and Figure 10.10 shows different samples for the bending tests. Parameters that could be adjusted were:

(1) To test with a distance per second or force per second
(2) The print direction
(3) The size of the samples
(4) The material
(5) The water percentage (%wt)

It was decided to use the universal testing machine in a way that the applied force increases with the same amount each second. This because the ceramic samples are brittle and a distance per second would cause less reliable results. The force would increase exponentially since there is less elongation with brittle materials before failure.

Because the data is only based on a first test, only the observed fracture pattern and

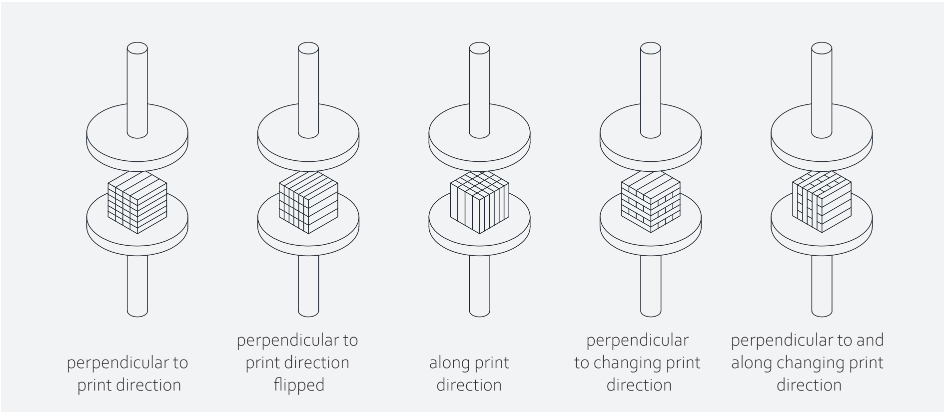


Figure 10.9 Possible compression test layouts

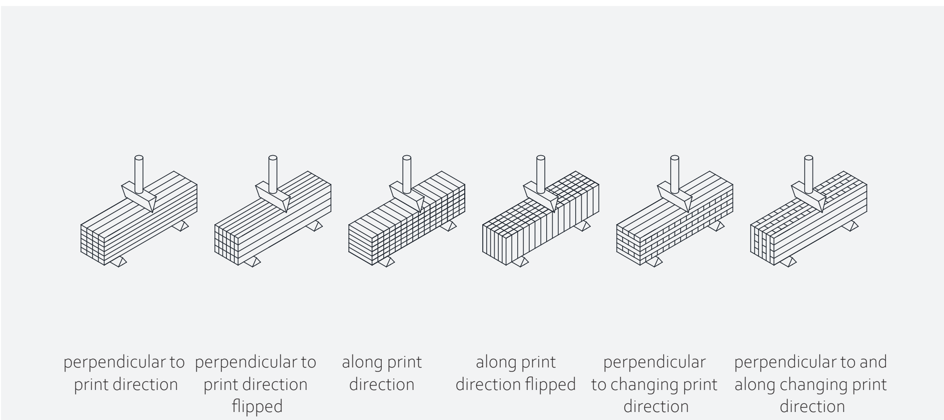


Figure 10.10 Possible tensile test layouts

data on the strength will be discussed. However, more tests need to be performed for verification of the assumptions made, especially with regards to different material mixtures.

Samples are printed to see the correlation between the material's performance when processed with robocasting and the production process. These samples differ in size and layer direction. Figure 10.11 shows a sketch of the samples and Figure 10.12 shows how the G-code describes these paths. Both images are just a representation of the final samples. Different material compositions can lead to different material distribution within the layers due to the viscosity and processability of the material mixtures. Experiments with different material mixtures and samples were examined.

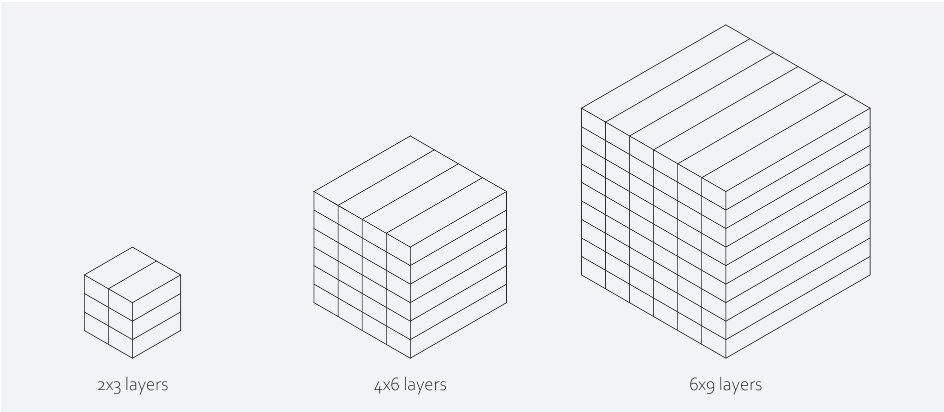


Figure 10.11 Scaled family of samples
The cubes have the same print direction. Note that they can be rotated to adjust the test direction.

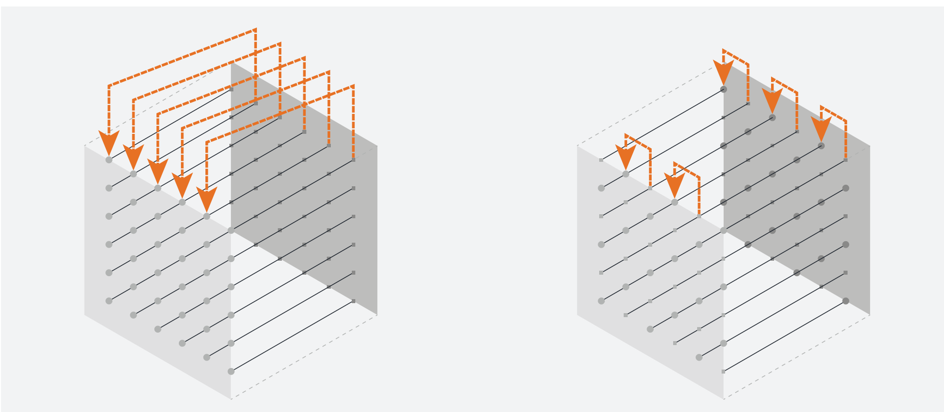


Figure 10.12 Producing the test specimen with code for FDM

10.2.1 Producing samples

Samples had to be made before the tests were carried out. As shown in Figure 10.12, a path is drawn manually for these samples, which allows the cubic samples to be produced according the desired resolution and size. This was done without an automated slicing tool, but to exactly control the position of the path and the deposition rate of material along this path, the script had to be extended with material extrusion rates manually.

The expected shrinkage could be predicted because the material had been used before. The printed sample parts must therefore be larger to compensate for the shrinkage during drying and firing. Figure 10.13 shows a schematic representation of the production steps

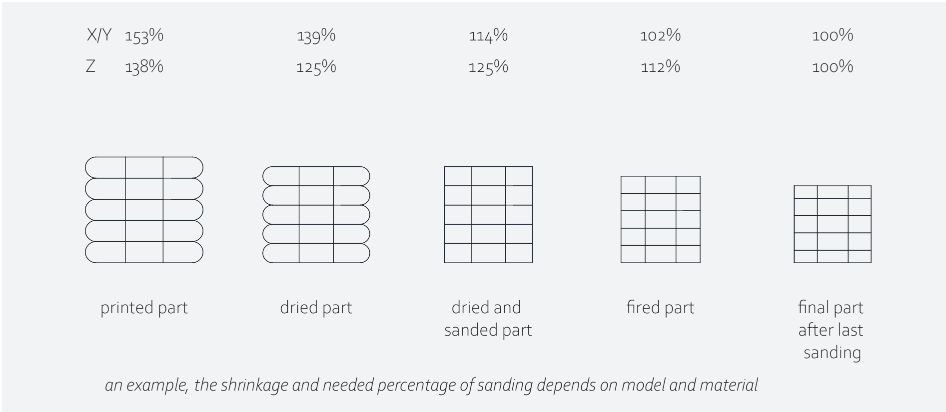


Figure 10.13 Example of production steps to produce test specimen

Figure 10.14 Printed test samples before firing

carried out to produce the cubic samples. The same steps are involved for the beams printed for the three-point bending test.

The steps involved after firing at lower temperatures are sanding the samples in the right shape before firing at higher temperatures and final sanding thereafter.

Shrinkage influences the size. The material mixture influences shrinkage more than the printing technology itself, because the influence of the printer accuracy range is less than the almost 10% shrinkage of the samples. Since it was known that the samples for the structural tests would shrink, they were printed slightly larger; and were then milled close to the desired size after the biscuit firing. Thereafter the samples were fired again and milled in the final shape by removing thin layers of material as indicated in Figure 10.13.

Due to the experimental setup and dimensional restrictions of the samples, the samples were assessed before the strength was tested.

10.2.2 Structural assessment

The first results were an outcome of tests carried out at the Institute of Structural Mechanics and Design (Fischer, M., 2017). The results of the compressive and tensile strength tests are presented in Figure 10.16. The first conclusion is that AM influences the structure of the material in the samples. If there is an anisotropic behaviour of the layers of AM, this becomes especially visible when non-perpendicular loads along the print direction are applied to the specimen. The reason why this would occur seems to be the layered production technology. Table 10.1 and 10.2 show the exact results of the compressive tests

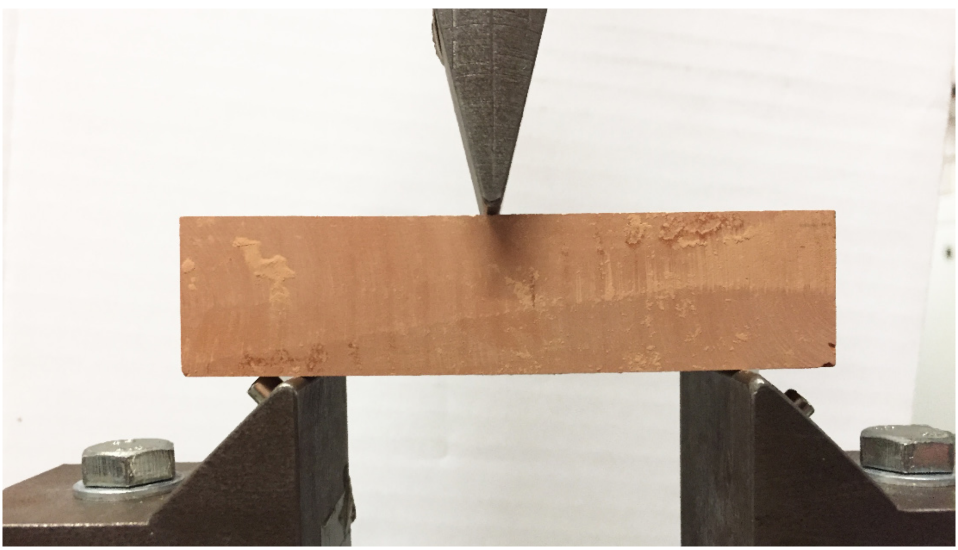
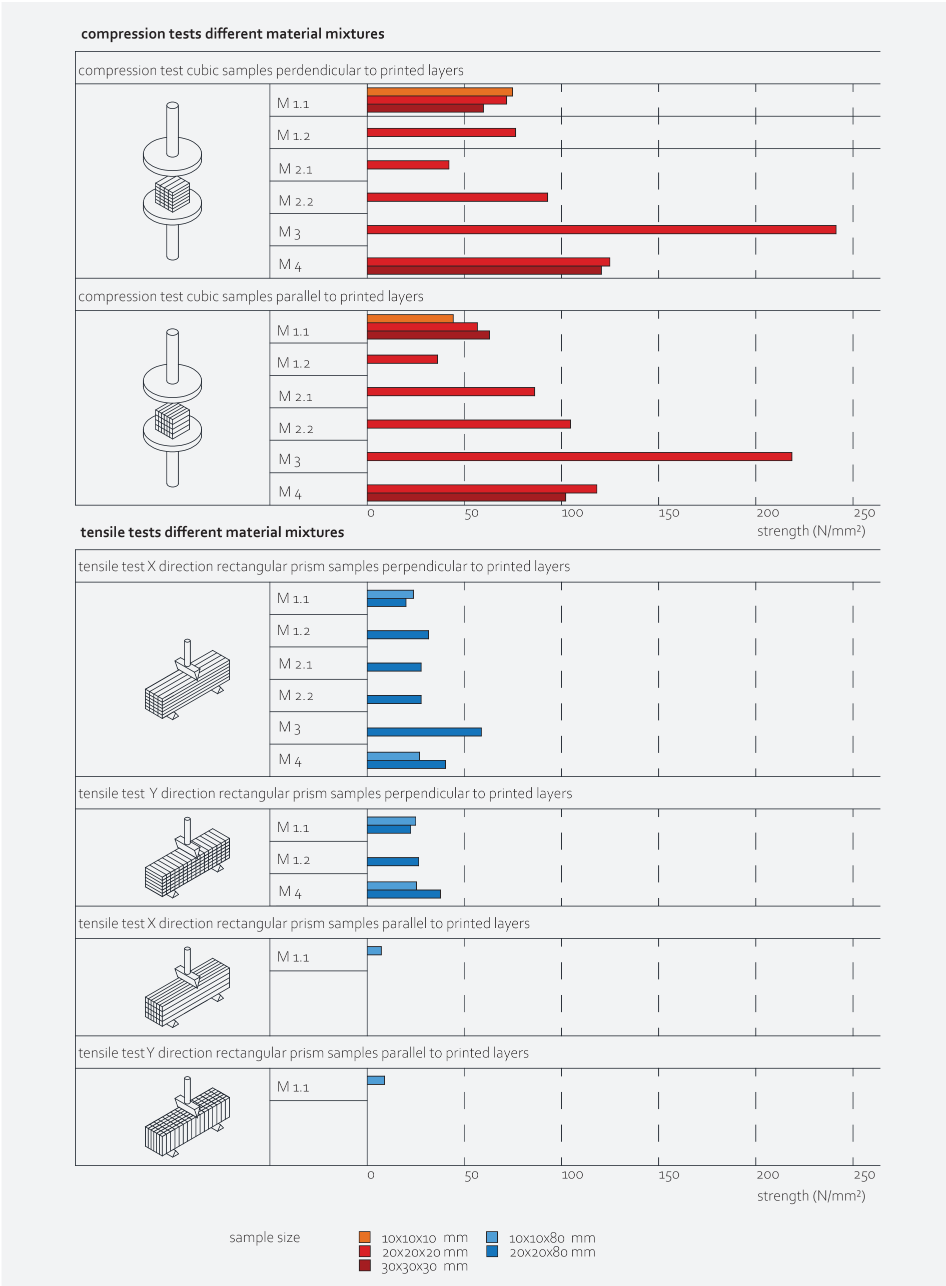


Figure 10.15 Tensile strength test



Results obtained from M. Fischer's (2017)supervised research project.

Figure 10.16 Compressive and tensile strength test results

Figure 10.17 Tested sample
Typical mechanism of failure observed while samples were tested along the print direction. Delamination between the layers.

and the result of the bending tests performed.

There is a remarkable difference in performance of material 3 in comparison to the other three mixtures. This material was darker and the material was more sintered during firing. This resulted in a stronger material.

As expected, the tensile strength is lower than the compressive strength and the test – partly parallel to the print direction – had a decreased performance in comparison to tests performed perpendicular to the print direction. Some anisotropic behaviour can be observed. Finally, larger test samples almost always performed less well than small samples. Fischer, M. (2017) assumes that imperfections play a significant role in the performance of the samples, it has to be assumed that the larger the samples, the more invisible imperfections could be embedded in the samples, which explains the lower performance of larger test samples. Also the porosity increases when more adjacent layers are printed (Cruz, P. J.S., Camões, A., Figueiredo, B., Ribeiro, M. J., & Renault, J.,2020, p. 15).

Looking at the failure mechanism of the samples, the test samples tested with compression perpendicular to the print direction often show a typical hourglass shape (Figure 10.17), while samples compressed partly parallel to the print direction seem to break across the layers (Figure 10.18).

The tensile samples broke at in unpredictable places when tested perpendicular to the print direction. For the samples that were tested parallel to the print direction, a failure mechanism was observed that corresponded to the samples tested on compression strength parallel to the print direction. The beam samples for the tensile tests broke along

Table 10.1 Compressive strength cubic sample

tensile strength beam samples in N·mm²							
size [mm]	mixture	1.1	1.2	2.1	2.2	3	4
X direction B1							
10 x 10 x 10		74.76					
20 x 20 x 20		71.84	76.47	42.13	92.82	241.23	124.92
30 x 30 x 30		59.71					120.45
X direction B2							
10 x 10 x 10		44.23					
20 x 20 x 20		56.62	36.32	86.28	104.58	218.47	118.28
30 x 30 x 30		62.88					102.23

Table 10.2 Tensile strength samples tested with a 3-point bending test

tensile strength beam samples in N·mm²							
size [mm]	mixture	1.1	1.2	2.1	2.2	3	4
X direction B1							
10 x 10 x 80		23.84					27.02
20 x 20 x 80		19.97	31.67	27.79	27.78	58.70	40.41
X direction B2							
10 x 10 x 80		25.12					25.41
20 x 20 x 80		22.52	26.62				37.72
Y direction B1							
10 x 10 x 80		7.26					
20 x 20 x 80							
Y direction B2							
10 x 10 x 80		9.06					
20 x 20 x 80							

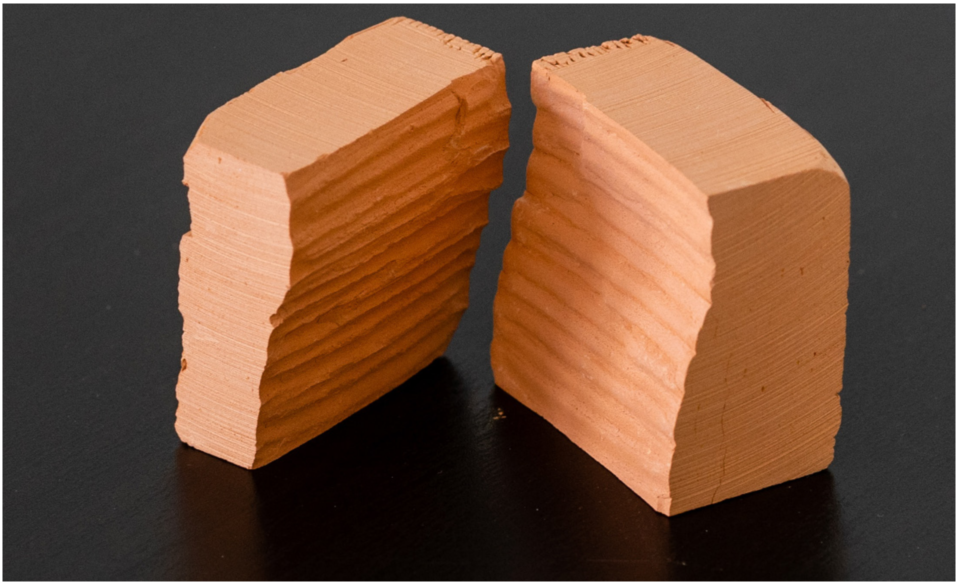


Figure 10.18 Tested sample
Typical mechanism of failure observed while samples were tested perpendicular to the print direction. The sides of the samples broke of during compression and a typical hourglass shape was observed.

the printed layers, as can be seen in Figure 10.19 and Figure 10.20.

Even though the batch of samples tested is not large, it offers a general understanding of the performance and indicates that a certain anisotropic behaviour should be expected. For further understanding of failure mechanisms and strength, and to obtain more accurate results, more test samples have to be produced and tested. It is important that the quality of the samples can be replicated to eliminate an important influence by the parameter related to print quality, that can cause a large spread within the test results.

Figure 10.19 Tested beam

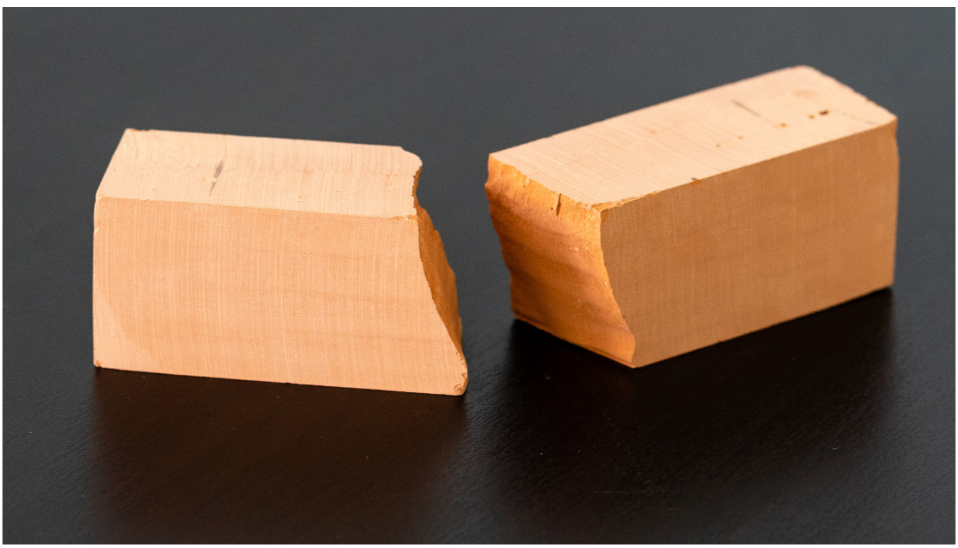


Figure 10.20 Tested beam
Typical mechanism of failure observed while samples were tested in a three point bending set-up along the print direction. Delamination between the layers.

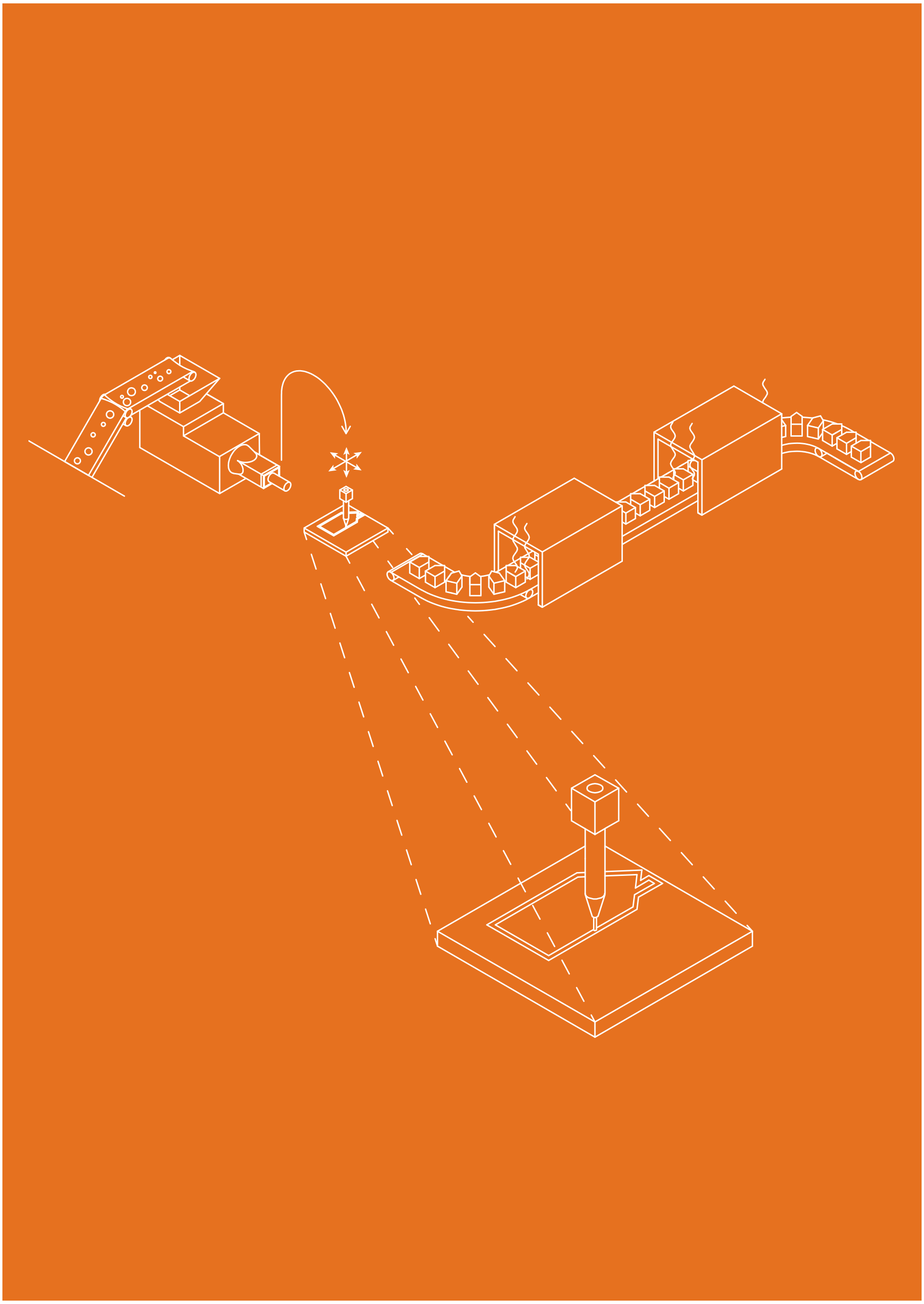


Figure 11.1 AM as part of a production chain

11 Printer design

The demands formulated in the previous chapters are used to design the robocasting-based printer. The printer consists of the manipulator and peripherals to facilitate the nozzle's movement, and the extrusion mechanism itself, including the nozzle, which deposits the silicate ceramic (clay). The design of the robocasting AM process for clay materials is divided into the design of the manipulator and the design of the extrusion mechanism.

This chapter describes the design of the manipulator. Figure 11.2 shows a schematic layout of robocasting without a specific manipulator. In order to process the material, it is important that the movement and material extrusion are synchronised. Often, a G-code is used to describe the path and the amount of material that has to be deposited by the robocasting printer.

11.1 Controller and file handling

The speed of the movement is used as input for the material deposition of the extruder. The preferred amount of material deposited can be set in the G-code or it can be controlled by the controller of the printer. The direction and place where material needs to be deposited is controlled by the code and loaded into the manipulator by using a position in the Euler coordinate system, a speed and an extrusion value. For manipulators that only have 3 axes, only the X, Y, and Z value of the Euler coordinate system are used. The extrusion value defines the amount of material that should be deposited between two points

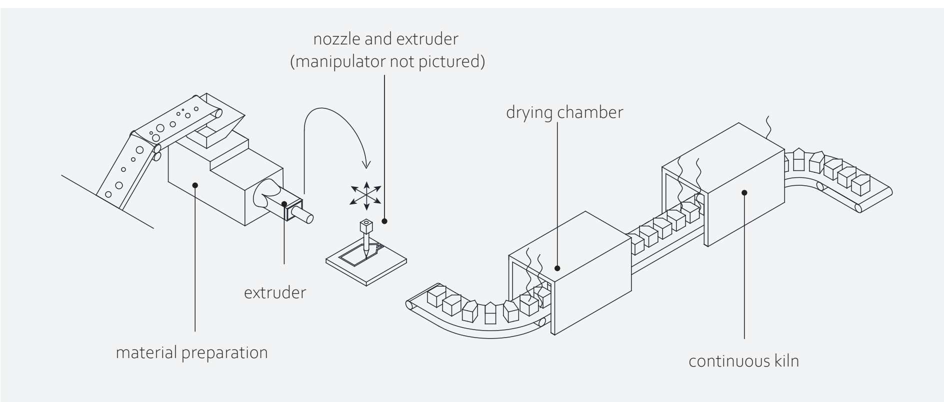


Figure 11.2 Schematic production steps

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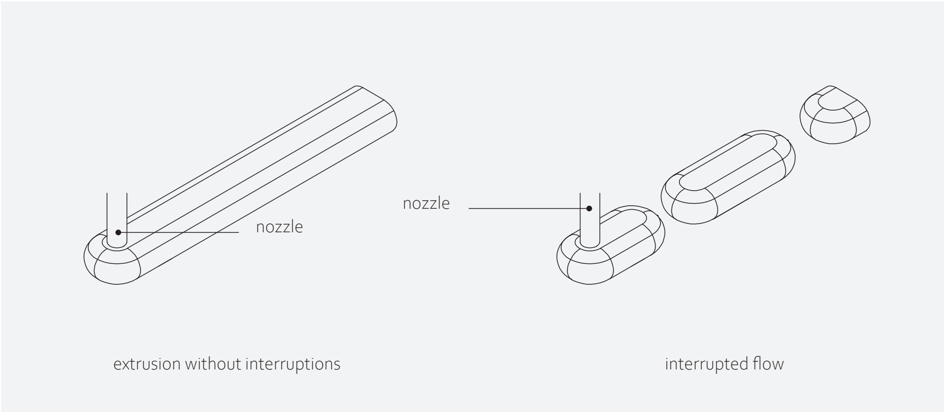

Figure 11.3 Extrusion quality

or at a coordinate. A simple code to translate 10 in Y direction with a speed of 100 and an extrusion of 10 looks like this:

(1) X0 Y0 Z0 α0 β0 γ0 F100 E0
(2) X0 Y10 Z0 α0 β0 γ0 F100 E10

In these lines and additional values of the code, X, Y, and Z define the position of the tool's centre point (TCP) and α, β, and γ define the angle of the TCP, which are controlled by additional axes 4, 5, and 6 of the manipulator.

F and E are additional values and indicate that, during the translation in Y direction with value 10, an amount of material 10 (E) is extruded with a travel speed of 100 (F). This value for the material can be an absolute or a relative value, a value that represents the exact amount of material, or just an number of revolutions of an actuator in the system. The code layout depends on the controller and preference of the programmer.

A relative code shows a total of the extruded material at each point so far. During development, this clearly displayed the increasing amount of material extruded during the process. Any coding errors were easy to find, which would be more difficult with servo motor positions only.

To additively manufacture the desired forms, the 3D model therefore needs to be translated into commands that can be processed by the printer. The translation of the G-code to the printer's language is done with a CADCAM software. The controller of the printer follows the code and the movement and material extrusion are controlled by the amount of revolutions and final position of the servo motors.

The motors of the manipulator as well as the motors on the tool need to be synchronised. The synchronisation is handled by the controller of the printer that not only controls the speed and final position, but should also control the spin-up and down-time of

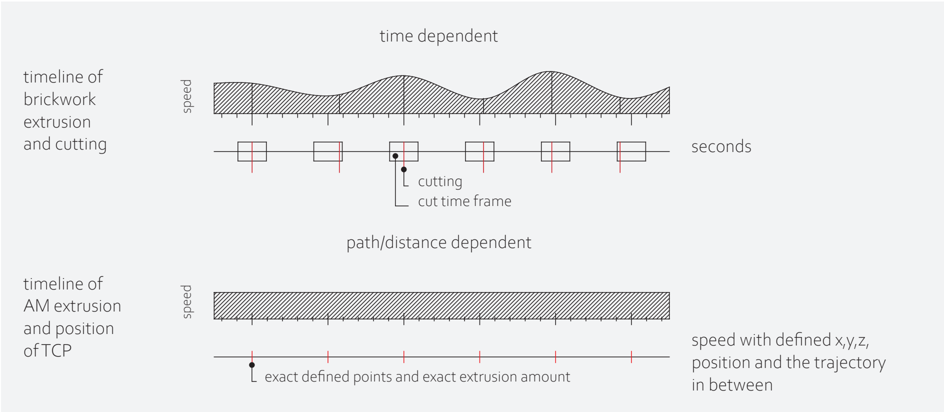

Figure 11.4 Extrusion speeds and cutting
The speed needs to be synchronised for AM, since fluctuations cannot be compensated for in the next production step.

these servo motors to keep them synchronised at any time.

The speed needs to be exactly synchronised for AM. Compare the result of good quality and interrupted extrusion in Figure 11.3. This is inherent to additive manufacturing by extrusion. Fluctuations cannot be compensated for in the next production step. When extruding standard bricks that are cut after they are extruded, the cutting can compensate for fluctuation in the extrusion speed. Compare the two lines in Figure 11.4.

11.2 Movement

The main part of the system is the extrusion mechanism which is attached partly or completely to the manipulator. The manipulator moves across the print bed. However, the print bed itself can be moved, too. In this case, the extruder is fixed and the print bed is moved by the manipulator, or both the print bed and extruder can be synchronized and form one unit that moves together. So the manipulator can be a portal/gantry frame, a robotic arm, a moving print bed or a combination of these. Table 11.1 shows a comparison of the two main manipulators, a gantry and a robotic arm.

A portal frame is less flexible, since the size of the work object is limited and harder to extend than with a robotic arm. A portal frame is preferred in the case of a heavier extruder mechanism because its accuracy can be higher than that of a robot arm. The point to point accuracy of a robotic arm (e.g..an ABB IRB 6640-235/2.55 robotic arm (ABB, 2019)) has a position repeatability of 0.05 mm and a path repeatability of 0.66 mm.

This means that the manipulator is very precise regarding its point accuracy but less precise between these points. A G-code normally consists of many points close to each

Table 11.1 Manipulator characteristics

manipulator	gantry	robotic arm
accuracy	high	"point to point high, path accuracy less"
movement	the layout determines the free movement	more freedom due to the combined 6 axes
tool weight	A gantry is very stable and can move heavy extruders easily.	The payload and centre of gravity of the payload determines which robotic arm can be used. The offset of the TCP influences the accuracy too due to the additional lever.
print bed size	The size of the print bed needs to fit underneath the gantry. The size is determined by the size of the gantry.	The print bed's size is limited to the reach of the printer, although a robotic arm can be mounted on a track easily which allows for a extension of the building platform in one direction.

other and the process will not be influenced by a less accurate path repeatability. A portal frame, however, has a higher resolution; 0.01 mm position repeatability is not uncommon due to the use of (precision) ball screws.

Portal frames have three or five axes while robotic arms have four or five (depending on what system the brand uses for so-called palletizing robots) or six axes, which can position the tool centre point (TCP) at any point according to Euler angles.

Three or four axes are sufficient for printing perpendicular to horizontally aligned objects. More complex forms that require printing perpendicular to a curved object require a six axes robotic arm, if the tool itself has no additional axis.

A portal frame has a horizontal beam perpendicular to the X-axis of the machine, which regulates the Y-translation. If the height is set by a Z-translation of the horizontal beam, this will limit the free height between the printed object and the portal frame. A sine wave along the Y-axis may not be performed without a collision with the printed part (compare the possible movements in Figure 11.5). Therefore, it is preferred that the extruder height is controlled by a movement of the Z-axis in the direction of the horizontal beam itself, so only the nozzle moves in Z-direction without the beam on which the Y-translation takes place.

The sixth axis of a robotic arm rotates the tool around its sixth axis. In most portal frames this axis is replaced by the motor of a milling device. If the nozzle has to be able to turn to follow the corners, an additional axis is needed to control this. This is the case both with a robotic arm and with a portal frame.

The reach of the robotic manipulator determines the building volume. A robotic arm can be placed on a track to increase the building volume in the Y-axis. A portal frame, in

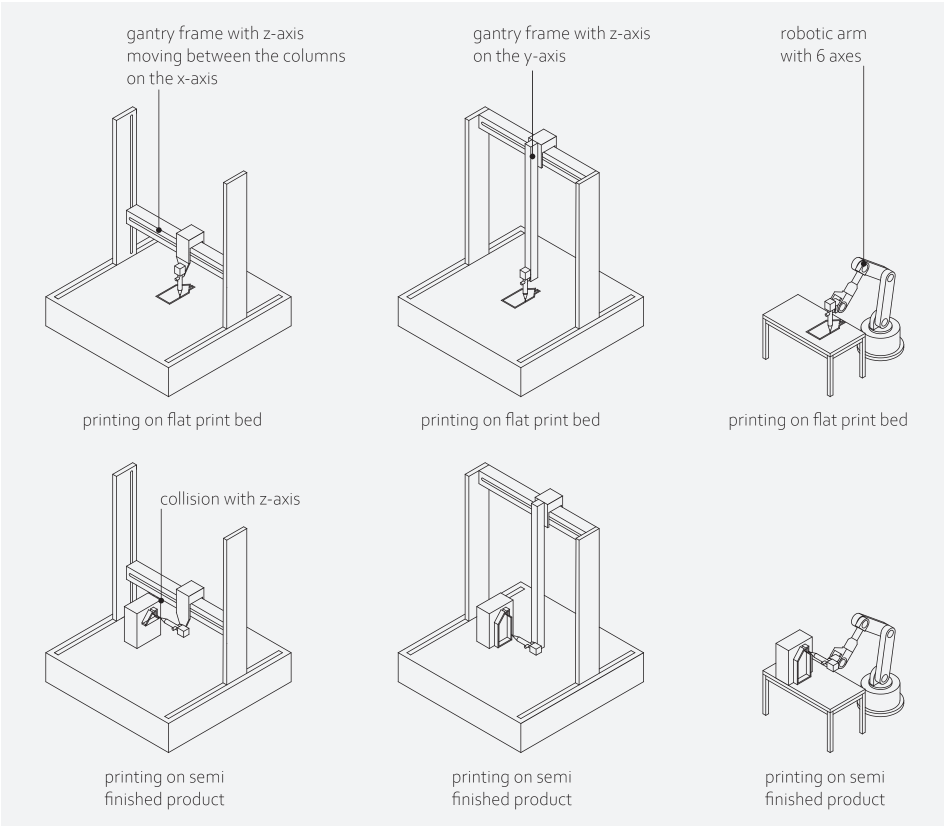

Figure 11.5 Gantry and robotic arm set-up

comparison, can be extended along the X or Y-axis by replacing the spindles and frame profiles.

The portal frame is also a more modular system because the axes can be added separately, but a robotic arm can also be a part of a bigger system. The robot arm can be put on a rail and the print bed can be moved and scanned where after the robot arm can continue printing on other parts of the print bed. This scanning can be replaced and controlled by an external axis, which moves the print bed. The print bed for printing ceramics probably has a limited size because large products will break during drying or firing and not because of limitations of the robotic arms and gantries.

11.3 Controller

To control the complete 3D printer, either the main controller has two functions or two controllers are needed. This is caused by the market. The producers of robotic arms work with a relatively closed platform. The movement and accuracy are only guaranteed if their controlling system is used, which can communicate with other devices by use of industrial communication standards. Even though there are initiatives that work on an integration of all controllers, this is not yet widely spread for robotic arms. Gantries are often based on customised solutions, where additional integration has taken place. In a preliminary design phase it is therefore likely that not all controllers can be integrated.

The controller of a 3D printer regulates the position of the manipulator with servos. The path and extrusion is controlled by the initial G-code and read by the controller of the manipulator. The second controller, a programmable logic controller (PLC) monitors the process by reading sensors, for example from the manipulator and the extruder. If necessary, the second controller can adjust e.g. the print speed or initiate tool maintenance scripts to flush the print head by sending signals to the first controller which acts on this input accordingly.

As described, there is a certain job distribution between the controllers. The main controller [a PLC] is the lead and the master, while the robot controller is the follower in the entire system, acting on input from the master. The master controller facilitates the human-machine interface (HMI), too. The HMI consists of buttons and indicators that show the machine's state. Safety is also handled by this PLC. Signals of sensors and scanning devices provide the master PLC with the necessary information to respond to unsafe situations, which allows for an immediate emergency stop of the machine.

Print file processing

Some flaws that could occur with robocasting are listed in Table 11.2. Precise dosing of the material is important to obtain replicable results.

Before the (sliced) model can be sent to the robot, a list of commands for the robotic arm is generated with a CADCAM software. Based on the model and the capabilities of the robot, the software defines the movement of the manipulator by generating a code for the robot's controller. The code contains the position of the TCP but can be extended with information which controls the amount of material that is extruded at individual paths and for different nozzles (Figure 11.6) and, for example, the direction of the tool's print nozzle. The quantity of the material will be translated into a precise number of revolutions of a motor by the controller and will be referred to as an absolute position of a servo motor for the position of the extrusion mechanism.

The code that is sent to the controller of the robot could contain all movement related code, including pre and post print movements. However, the pre and post print movements

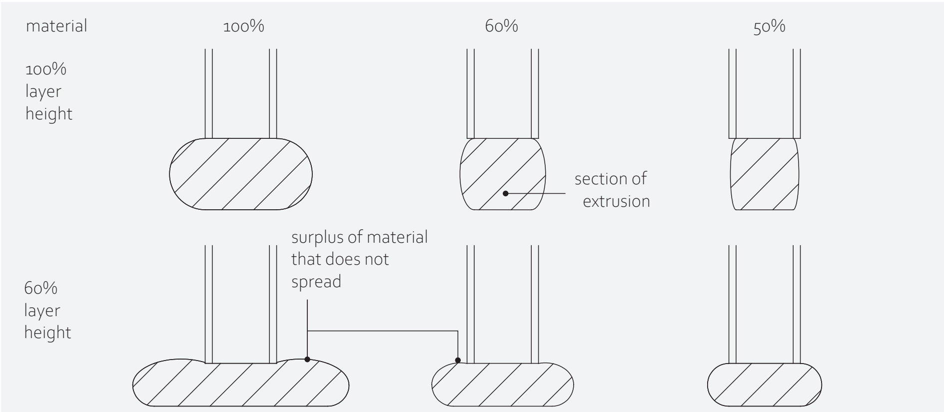

Figure 11.6 Amount of extruded material in comparison to layer width and layer height

Table 11.2 Known possible flaws and the proposed solution for robocasting

flaws	solution printer manipulator
accuracy of the print	improve printer accuracy
replicability of the print	improve printer accuracy and extrusion mechanism use sensors to monitor the printing process
asymmetric drying	control the moisture content in the print bed active drying of the printed component

as well as material information can be stored in separate programmes which are activated by referring to them in the G-code. These separate programmes can also be activated for a material change, or when the material needs to be refilled according to sensor measurements, for example.

To control the flow, the machine needs to know when it needs to extrude material and when not to. This can be realised by using the G-code to define the amount of material extruded, but also by a “smart” controller based on coordinates and a Boolean that defines whether material has to be printed or whether it is a travel movement.

When the geometry is sliced, the software can provide either the extrusion values or just a code when the extrusion should start and stop. In the latter case, the controller of the printer calculates the amount of material by calculating the distance between the points. This limits the complexity of the slicing on forehand but hinders different extrusion widths out of one nozzle. When more material is pushed through the nozzle, the extrusion width can be increased. This becomes helpful when sharp corners are part of the print path. There are six types of corners:

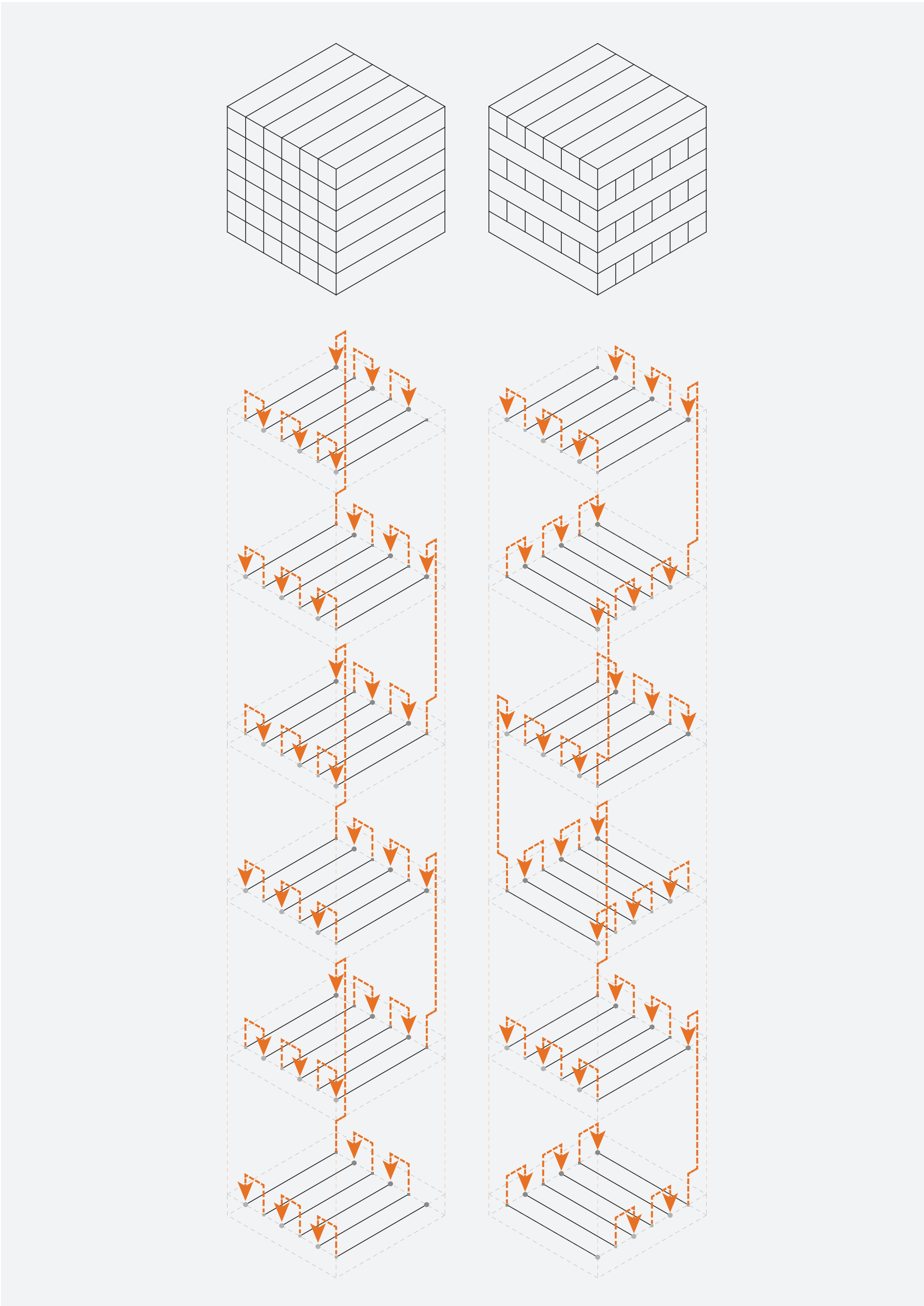

Figure 11.7 Print paths

(1) 0-45 degrees with a radius less than 0.5w
(2) 45 - 90 degrees with a radius less than 0.5w
(3) 90 - <180 degrees with a radius less than 0.5w
(4) 0 - 45 degrees with a radius larger than 0.5w
(5) 45 - 90 degrees with a radius larger than 0.5w
(6) 90 - <180 degrees with a radius larger than 0.5w

As long as the path of the curve has a diameter [r] of half the extrusion width or larger, the area of the material deposited in this curve's path is the same as a straight path, with the path's radius, r, and the path's width, w.

$$\text{area path } 90^\circ \text{ circle} = \frac{\pi(r+\tfrac{1}{2}w)^2 - \pi(r-\tfrac{1}{2}w)^2}{4} = \tfrac{1}{2}\pi \cdot r \cdot w \tag{11.1}$$

$$\text{path length } 90^\circ \text{ circle} = \frac{2\pi \cdot r}{4} = \tfrac{1}{2}\pi \cdot r \tag{11.2}$$

$$\text{surface area of a path with the length of a } 90^\circ \text{ circle} = \tfrac{1}{2}\pi \cdot r \cdot w \tag{11.3}$$

When the described path has a corner radius less than half the extrusion width, the surface area of the corner is less than 1⁄2 π·r·w, causing an overlap in the extrusion path if the same amount of material is extruded along the complete path defined in the G-code (Figure 11.8). The surface area therefore needs to be calculated accurately.

To calculate these extrusion values with the robot's controller has the advantage that less code has to be streamed and saved on the controller; however, processing capacity in the robot's controller is required.

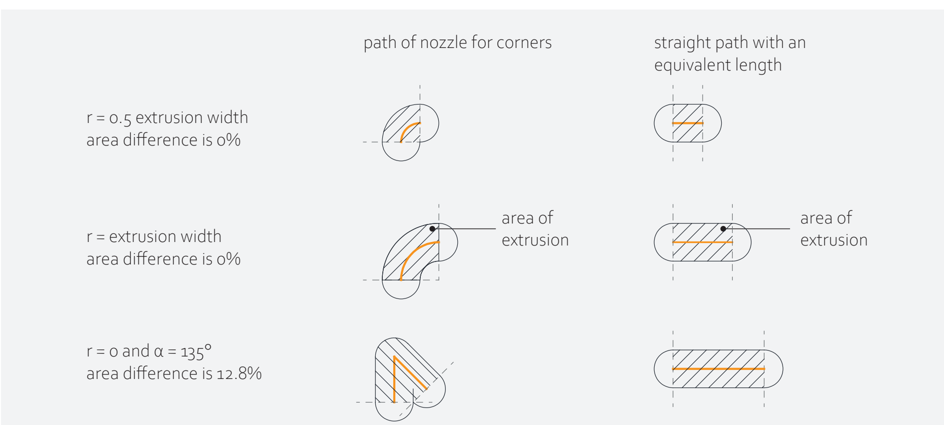

Figure 11.8 Corners and material volume of extrusion

Control of the extrusion width at certain points is helpful, for example if infill material between a perimeter is needed. By dividing the space in a whole number of lines, the print path's width can be slightly altered over the extrusion value. A PLC will not be able to calculate these amounts as adequately as a slicing tool on a PC can do.

If this is controlled by the controller, it can be controlled with a factor of extrusion. However, manual coding of the extrusion will make the programming more complicated and if additional code is necessary before or after printing, an additional command generated by the slicing software is preferred.

11.4 Print bed

The print bed that was used during the preliminary phase of this research was made of gypsum. Gypsum can have the same moisture content as the clay paste that is printed on it. The principle of using gypsum for shaping clay is therefore common for pottery.

However, for replicability and control of moisture the print bed needs to be improved. This can be done by placing sensors in the print bed that monitor the moisture within and at the surface of the print bed. The material mixture can be adjusted, too, in order to reduce the moisture in the print bed and increase the print's stability. Material properties can be checked by performing a DTA and by performing a Pfefferkorn test of the material batch to assess the material properties based on the outcome of the tests. These results can function as an input for the print settings.

During the print, it is advantageous if the print bed is moist. However, during drying this causes an uneven moisture content in the printed part because the print bed is a source of moisture which is assimilated by the first layers of the print. Together with deformation caused by its own weight and internal stress, the lower part of the models became wider. It contained a higher moisture content over a longer period, which causes sagging of the 3D printed green body in the lower part.

The print bed could also be shaped as a three-dimensional object to act as formwork. In this case it is important that the printed green body can shrink without being hindered by the formwork. This formwork should be supporting but also allow to deform during drying. Therefore the use of a 3D-shaped print bed may eliminate some of the advantages that AM offers.

11.5 Sensor system and logging

The physical layout determines the print size, the print resolution, and the geometry that can be printed. However, to control the print process for improved print quality and replicability, a process that guarantees that the same product can be made without flaws needs to be engineered. If a process produces different products or uses a material which

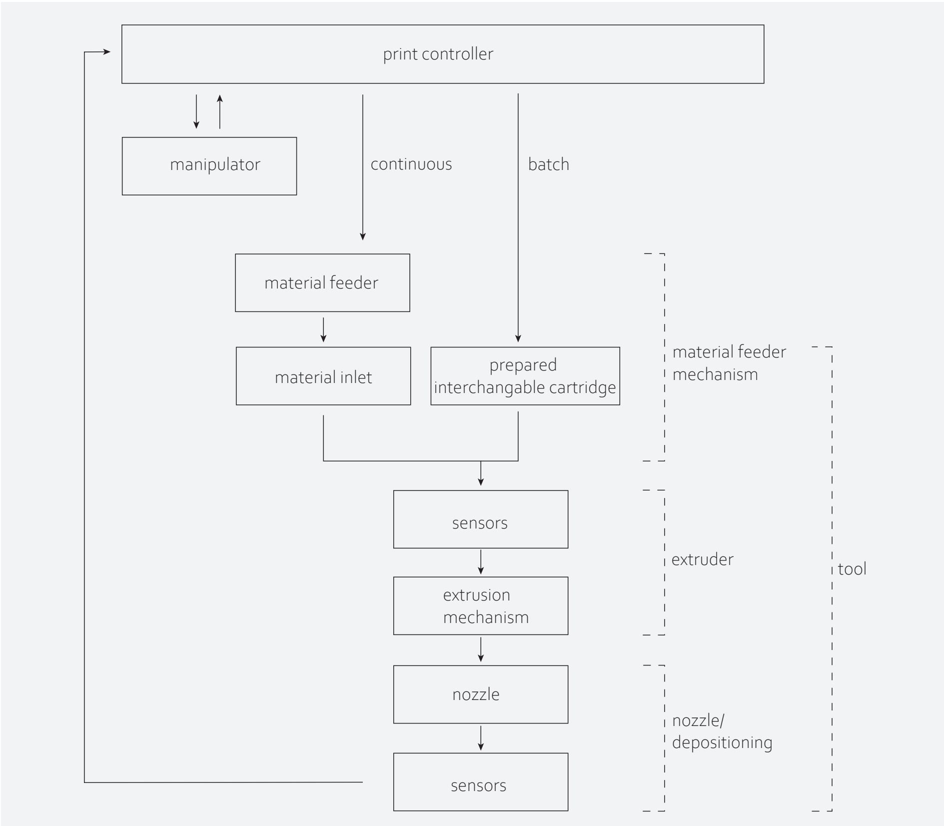

Figure 11.9 Layout of the printer set-up

could change slightly over time, additional information of the process by use of sensors and logging helps to increase the overall performance. Sensors can be used to log data during the print and to control the printing process itself by providing real-time process information to the manipulator and tool. Some sensors are incorporated in a layout diagram (Figure 11.9).

The extrusion pressure at the nozzle can provide information regarding the uniformity of the extruded clay. Air gaps will result in a reduction of the pressure and could be compensated for, or the process can be stopped.

A variety of sensors can be used:

(1) Pressure sensors
- Nozzle
- Material cartridge
- Material feeding mechanism

(2) Temperature sensors
- Nozzle
- Room

(3) Humidity sensors
- Room
- Print bed

A moisture sensor in the print bed could be used to log and optimise the humidity by comparing the measurements to the deformation of the first layers of the print.

Video imaging of the nozzle during the printing process could be used to trace back errors and compare measurements of the sensors to images of the extrusion at any moment.

Logging of all data can take place based on the data available from the servo controllers of the printer. To analyse and improve the printing process, logging is a tool that can provide valuable information, and therefore the information of additional sensors (and video imaging) needs to be embedded in the same log file to see relations and learn to predict the process.

11.6 Layout

The printer's layout depends on the weight of the extrusion mechanism and the stability of the material after extrusion. For plastics (immediately solidifying materials), moving the print bed is a possibility. For more liquid materials, moving the print bed and introducing vibrations in the fresh printed part can lead to instability and a collapse of the model.

Building products printed out of clay would require a relatively large amount of material. The weight of this material can be carried by the manipulator, or the extrusion mechanism has to be split, to reduce the weight between the nozzle and the extruder. A flexible hose is then needed to supply the material. It is important to note that the hose introduces additional resistance in the extrusion process and may absorb water and should not expand under pressure. If the amount of material is not controlled before the nozzle and the extruder themselves, the expansion and relaxation of the hose can lead to inaccurate material extrusion. More information on how to control the material deposition is described in Chapter 12.

How the printer is assembled differs but the AM system layout for robocasting consists at least of the following parts:

(1) Controller
(2) Manipulator
(3) Extrusion mechanism
(4) Nozzle

(5) Extruder
(6) Material feeder
(7) The print bed

In regular desktop 3D printers, the extruder is moved by a portal frame mechanism. If a robotic arm is utilised, more complex paths can be printed because there is a chance that a portal frame could collide with the printed material to reach some points defined in the G-code. With a robotic arm this can be eliminated by programming the controller to avoid collisions with the printed model itself during printing.

A robotic arm is precise, but in general, a portal frame is more precise and more stable (Möller, C., Schmidt, H. C., Shah, N. H., & Wollnack, J., 2016 p. 390). A robotic arm's repeatability ranges from 0.03 - 0.1mm, but path accuracy is lower (Olabi, A., Béarée, R., Gibaru, O., & Damak, M., 2010, p. 471). However, the accuracy of a robotic arm could be sufficient for processing clay, since shrinkage has more influence on the final shape than the accuracy of the robot in comparison to a portal frame structure. The tolerances of clay ceramic building components are larger than industrial components made from steel. In the detailing of building's, the tolerances should be taken into account if the design process is carried out adequately, next to the applicable building codes.

The control of the printing process and the printer can be realised with different setups. The actions required can be divided into these three steps in different ways. This depends on where the "intelligence" of the system is located.

For replicability, the process has to be controlled. In the favourable system layout, the manipulator controller should be able to intervene in the process if there are small flaws in the extrusion process and it should stop for assistance if the print fails. Table 11.3 shows the advantages and disadvantages of integrating functions in the controller. A system layout could consist of 4 steps:

(1) The 3D model is sliced by the software which provides the paths, the speed, and the desired amount of material.
(2) This G-code is translated to a file by CADCAM software that can be read by the printer's controller. The output of the slicing is processed to generate a code that can be read by the printer.

Note that this post-processing can also be done by the software on the printer's controller but will use additional calculation bandwidth on e.g. the PLC. A computer has more capacity for these calculations and the file can be simulated before it is sent to the printer.

(3) The controller of the printer translates the paths and extrusion to servo (or stepper) revolutions/movement.
(4) During the printing process, the controller controls the movement based on the generated G-code and feedback from sensors in the printer. Traveling speeds are

Table 11.3 Integration of functions into the machine's controller

implementation of functionality in robotic controller	how	advantage	disadvantage
extrusion	by calculating coordinates and determine material flow	less complex G-codes and less software involved	The controller cannot change layer width by use of controlling the extrusion amount. The calculations cost performance of the controller for which the robotic controllers are less effective.
nozzle direction	by coordinating the vector of the path	This is a movement related to the robot axis system and can be controlled by the robot.	Costs performance and there is no control in the pre print phase to adjust this.
safety	by reading safety sensors		
print process control	by reading sensors	this can reduce print failures	Costs performance if many calculations need to be made.
standard programmes	save on the controller standard movements	These commands can be started by the G-code and do not need to be embed in the G-code itself.	There is no control during preparing a file on these movements.

recalculated and adjusted if necessary

Which system is used depends on the application and the integration of the process within the overall production chain, as well as the extrusion mechanism. This could be a continuous process or a process with cartridges (Figure 11.10).

If the manipulator has to print, mill and scan, a robotic arm is the more flexible alternative, although a portal could provide the same flexibility if it is equipped with a tool-changer like a robotic arm.

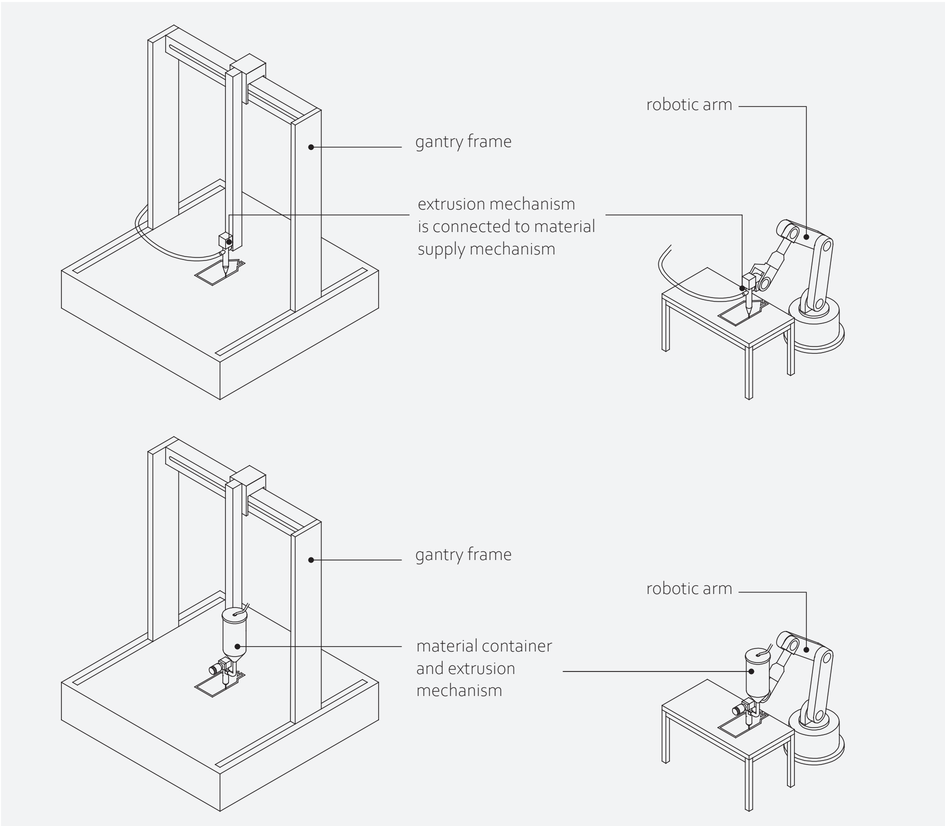

Figure 11.10 Tool layout of manipulator, continuous and badge extrusion

Figure 12.1 Printed rectangular bricks

12 Extrusion mechanism

The different extrusion mechanisms are compared and the design of an extrusion mechanism for processing silicate ceramic (clay) materials is described in this chapter.

12.1 Process demands for the extrusion mechanism

The amount of material deposited and the speed of the nozzle need to be synchronised to obtain good print quality. Even though the theoretical principle should work, there were some flaws visible with the desktop robocasting machine as mentioned in Chapter 5. The flaws directly related to the tool are:

(1) Air inclusion in the system
(2) Plasticity regarding the extrudability of the material
(3) Heat (increased temperature due to surrounding temperature and friction)

Table 12.1 shows the flaws of the extrusion mechanism related to the extrusion process and material. Chapter 9 indicates how the material influences the quality and how this can be improved. While the used extrusion mechanism had its influence on the quality of the extruded material, the flaws indicated in the table are used as input to improve the deposition of material.

12.2 Tool layout

Contrary to plastic extrusion technologies such as FDM, the amount of pasty material extruded with robocasting cannot simply be controlled by the RPM of a motor attached to gears that feed the material to the nozzle. The tool layout described involves the method to process the material.

12.2.1 Material feeder

There are two principles following which the pasty, high viscosity silicate ceramic material can be fed to the nozzle. The material can be prepared and stored in material cartridg-

D. de Witte, *Clay Printing*, Mechanik, Werkstoffe und Konstruktion im
Bauwesen 62, https://doi.org/10.1007/978-3-658-37161-6_12

Table 12.1 Known possible flaws and the proposed solution for robocasting

flaws	solution printer extrusion mechanism
air inclusion in the system	prevent air to be drawn into the print system by
plasticity regarding stability of the print	reduce force of extrusion on already printed layers improve the handling of high viscous materials
heat (increased temperature due to surrounding temperature and friction)	less friction at the extrusion mechanism remove heat from nozzle

es and extruded from these containers, or the material can be fed to the extruder by pumping the clay mixture through a hose. Both principles have advantages and disadvantages.

12.2.2 Batch size versus continues processes

Batch feed advantages:

(1) The payload on the 3D printer is reduced
(2) The material can be changed easily
(3) Cartridges could prevent additional cleaning of the system
(4) Support material could be printed by using a second cartridge
(5) Cartridges could be smaller to increase accuracy of the extrusion flow when positive displacement is used

Disadvantages:

(1) Change of a cartridge may cause an interruption and a seam in the printed part. (This is the case with continuous printing). When the part is printed by using retraction of the nozzle a change of cartridge could be planned during retraction.
(2) Cartridges need to be refilled
(3) Air initiated in the material due to cartridge change
(4) Additional loading time in a production environment during and between prints

Advantages of continuous feeding printing material are that the print is not interrupted, but there is less flexibility in material mixtures during the print. If a variation in density/material is desired with an continuous process, this could be realised by adding and mixing before extrusion in the nozzle.

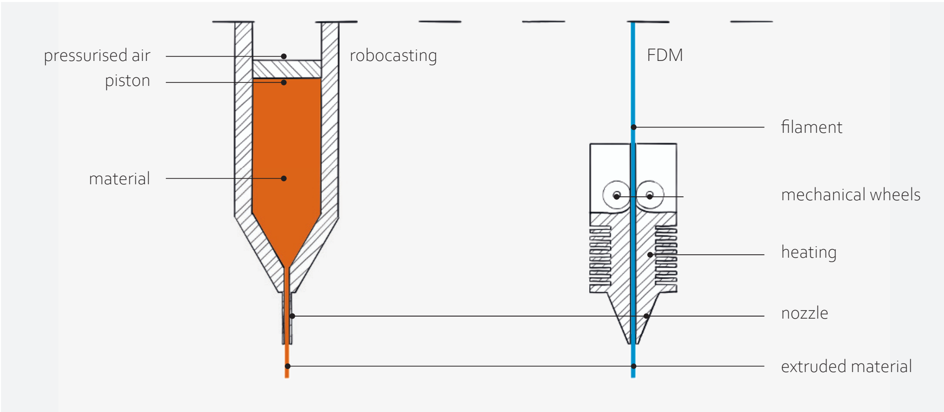

Figure 12.2 Robocasting compared to FDM extrusion

12.3 Robocasting dosing mechanism

Figure 12.2 shows the extrusion mechanism of a pasteous material and that of a filament. Unlike with filament, the amount of pasteous material fed to the nozzle cannot be regulated based on servo revolutions. The plasticity of the material and the technique used to process this high viscosity paste therefore needs to be controlled well. The controller of the printer will control the amount of material extruded. The mechanisms to control the extrusion that are used in industry are described.

Extruder

The way the 3D printing technologies are utilised differ. Robocasting is a dispensing mechanism. Dispensing material is widely used in different industries. From dispensing glue on a windscreen to tiny drops of solder on microchips. These Dispensing on Demand (DOD) or Extrusion on Demand (EOD) methods have been investigated over the years. There are several technologies used:

(1) Time-pressure dispensing
(2) Piston displacement
(3) Shutter valve-based dispensing
(4) Auger pump dispensing
(5) Progressive cavity pump
(6) Jetting dispensing

These technologies can also be used for AM of clay-based ceramics. The first five technologies are so-called contact dispensing technologies (Figure 12.3) since the nozzles touch

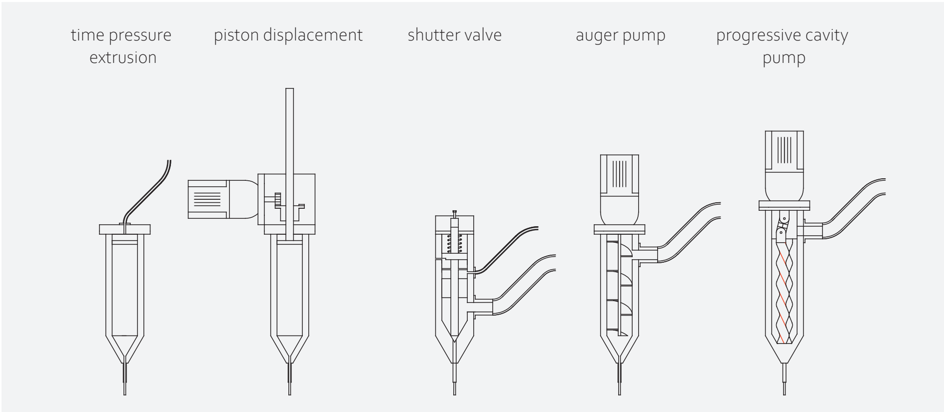

Figure 12.3 Different extrusion mechanisms

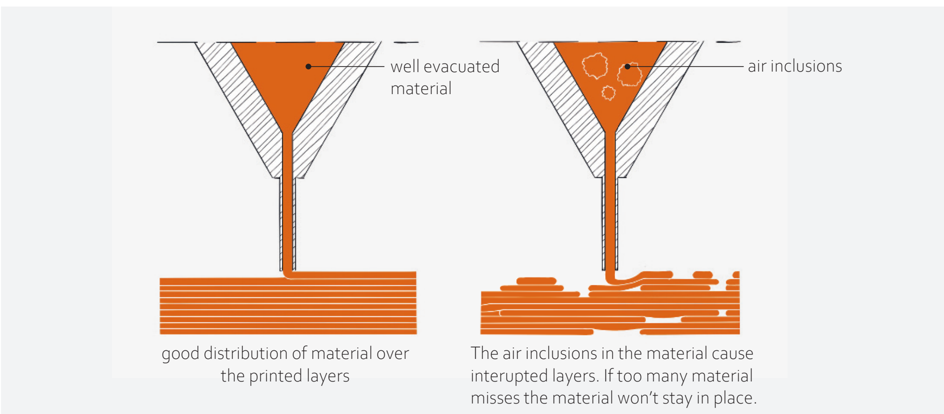

Figure 12.4 Interrupted extrusion

the substrate. In contrary, jetting dispensing is a non-contact technology because drops of material are dropped onto the substrate from a distance (Jianping & Guiling, 2004, p. 198). There are multiple ways to extrude material, but three mechanism could be used to extrude clay. Jetting dispensing is not further analysed because it is designed for specific materials that differ too much from the high viscosity paste material that is used in robocasting extrusion for silicate ceramics. The first five material extrusion mechanisms can be used for silicate ceramics, however, flaws due to air inclusions and interrupted extrusion (Figure 12.4) observed during the preliminary research phase need to be eliminated.

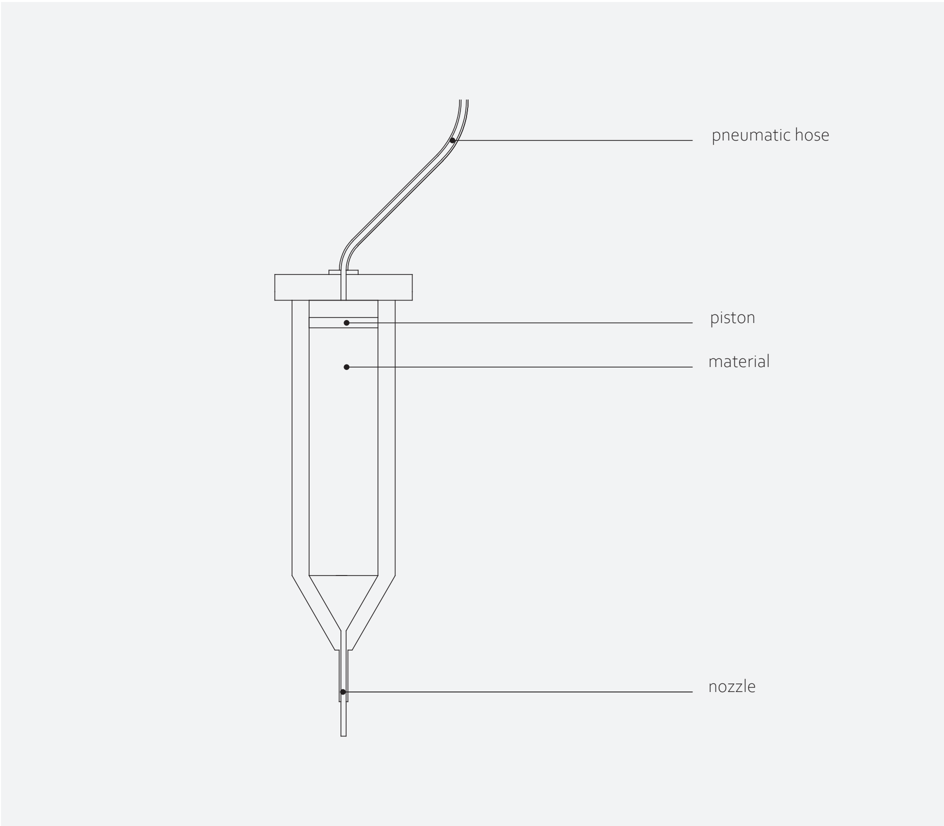

Figure 12.5 Time pressure extrusion

12.3.1 Time pressure extrusion

Time pressure extrusion is an extrusion method that uses a material cartridge. The material is pushed out of a the cartridge into the nozzle by use of air pressure. The extrusion amount is controlled by the air pressure and influenced by the viscosity of the material.

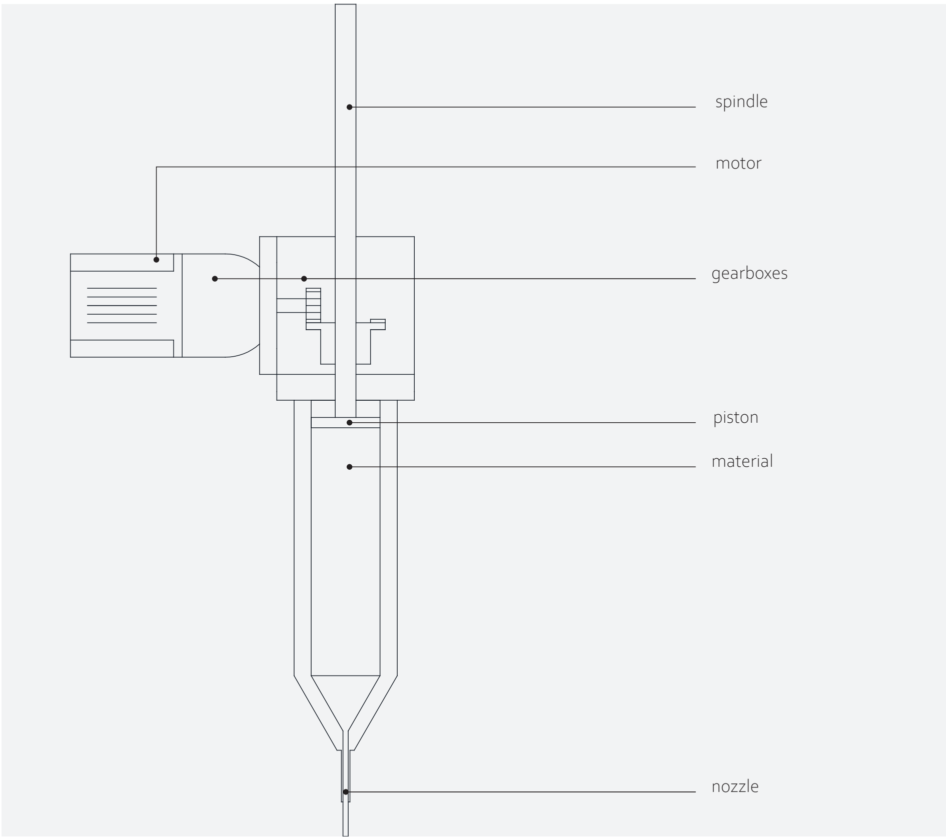

Figure 12.6 Piston displacement

12.3.2 Piston displacement

Piston displacement uses a piston or plunger to push the material through the nozzle. This is a true positive displacement system. Theoretically, a change in viscosity of the material does not influence the amount of material extruded with this mechanism (Jianping & Guiling, 2004, p. 204). The movement of the piston is, for example, controlled by the movement of a spindle driven by a (servo/stepper) motor with the position being controlled by an encoder. Air inclusions in the material, however, can cause the material to be compressed, which influences the accuracy of the amount of material extruded. This and the influence of air inclusions on alumina pastes is described by M. Li, Tang, Landers, & Leu (2013a); (2013b). The varying applied forces were measured, too, and a direct change in traveling speed of the piston was measured due to the decreased extrusion force needed. (This is noticeable when the spindle does not have enough torque and the mechanism becomes a non positive displacement, which could be prevented with a strong servo turning with a certain RPM).

It can be assumed that clay-based ceramics would exhibit some air inclusions, as well. These could be compressed and change the amount of material extruded over time. This becomes visible in straight lines printed with fluctuations in the thickness due to slow response on the piston's pressure. This has been demonstrated by use of a 610 and 406 µm nozzle for aluminium oxide paste with several additives (W. Li, Ghazanfari, Leu, & Landers, 2017, p. 203). This can be seen by the presence of a delay at the start and a tail at the stop as well, because the material decompresses after the servo motor stops applying force to the top of the material barrel. W. Li et al. (2017) show this with experiments and compare it with an extruder that uses a needle valve and an extruder based on a progressive cavity pump.

Removing air from the thick clay is difficult and the batches of material could therefore have different rheological properties. Thus, there can be a delay in the on-demand extrusion.

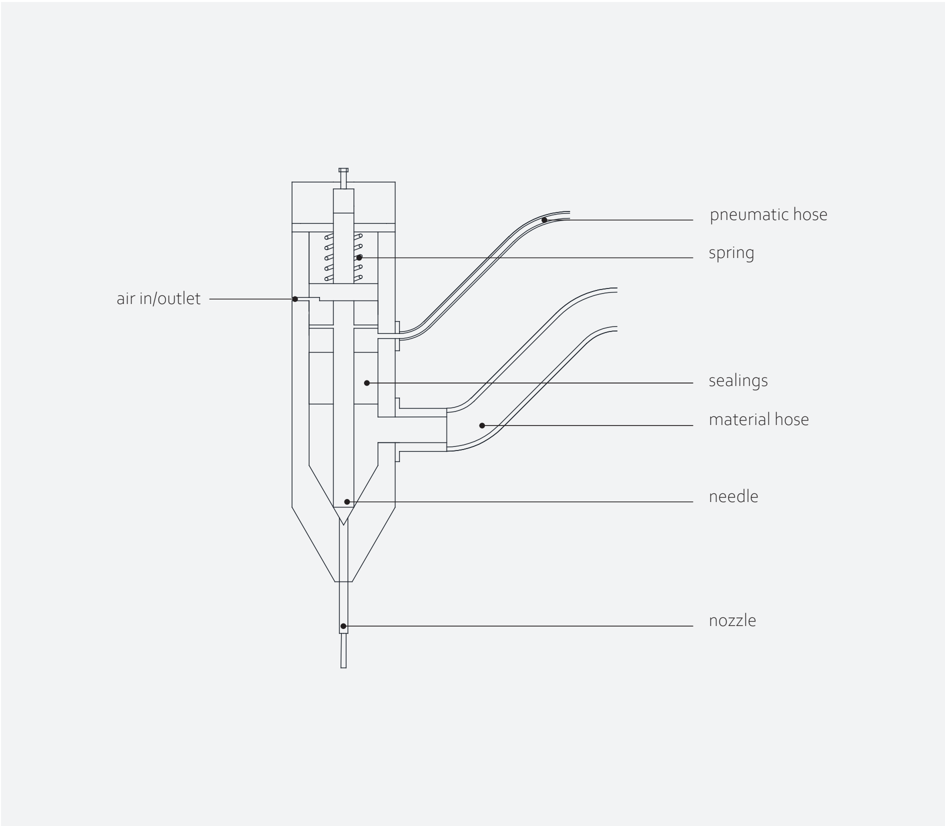

Figure 12.7 Shutter valve

12.3.3 Shutter valve-based dispensing

Shutter valve-based dispensing relies on a valve in the nozzle that can be opened and closed. The material in the material cartridge and system is pressurised to push the material through the nozzle when the valve is opened. The pressure and material's viscosity determine the amount of material protruding from the nozzle. Since the silicate ceramic material's properties can differ across batches, the dispensing process is difficult to control over time.

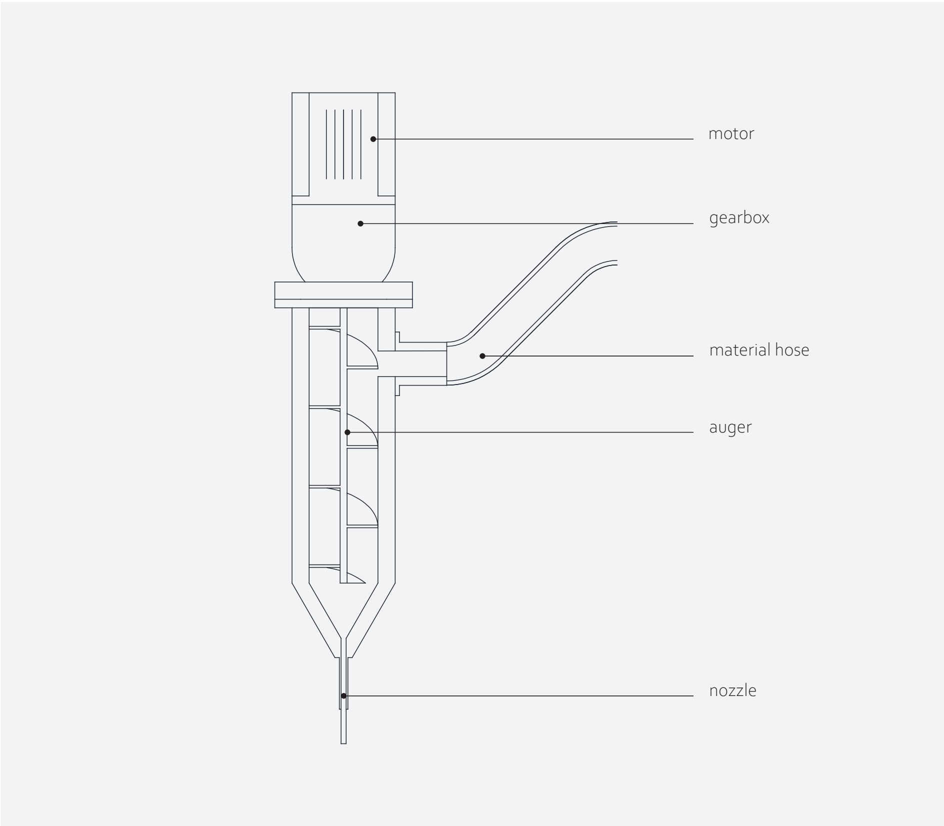

Figure 12.8 Auger pump

12.3.4 Auger pump dispensing

A pump based on an auger can pump high viscosity materials to the nozzle. It can, in contrast to the aforementioned mechanisms, be fed by a mixer. Therefore, the material dispensing process can be continuous. The auger's speed and material's viscosity determine the amount of material extruded. Since the extrusion mechanism also relies on the viscosity of the material, it is difficult to precisely control the amount of material extruded for materials with differing batch characteristics.

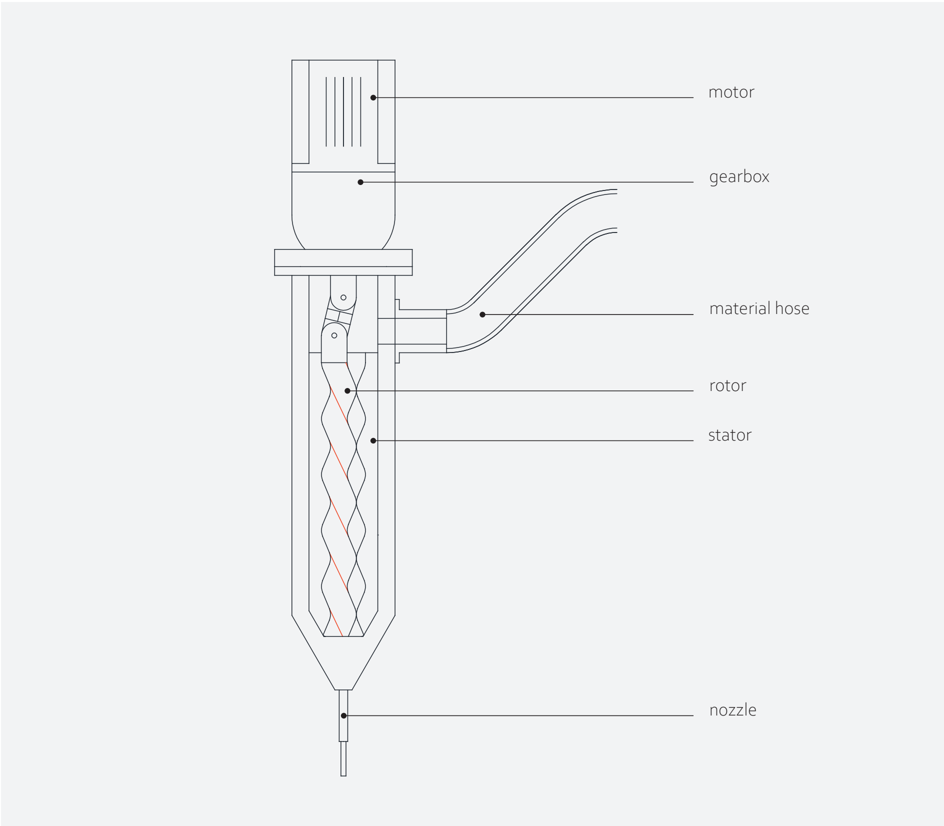

Figure 12.9 Progressive cavity pump

12.3.5 Progressive cavity pump

The principle of a progressive cavity pump was invented by René Moineau. The progressive cavity pump is also referred to as a Moineau pump or monopump.

The progressive cavity pump uses a stator and a rotor. The stator is often made out of a polymer and the rotor is made out of stainless steel. The polymer functions as wall and seal. The helix stator in combination with the eccentric helix rotating rotor transports material through a cavity along the axis of the pump. Figure 12.9 shows a section of a progressive cavity pump.

In the case of clay, the material is highly viscous and contains chamotte, which could be sharp, which can cause wear. The chamotte can get between the rotor and the stator, and the sharp particles act as an abrasive material on the rotor and roughen the surface of the stator when pushed in the rubber (Figure 12.10). This effect increases at higher RPM due to increased forces and friction.

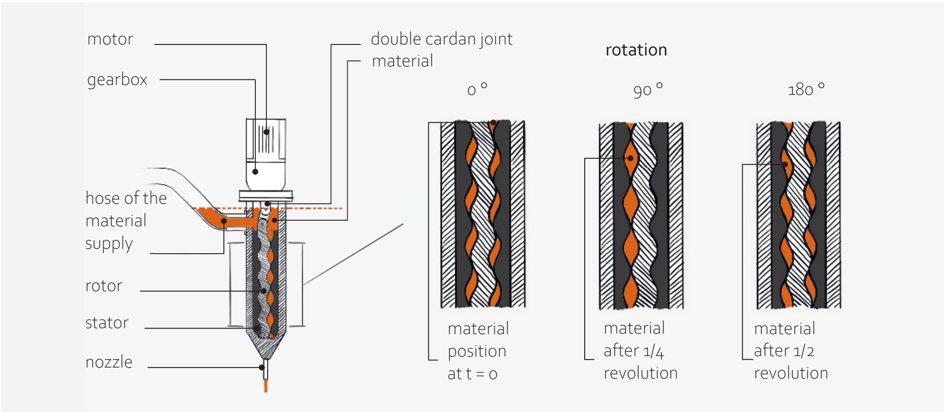

Figure 12.10 Progressive cavity pump functioning

12.4 Material dispensing speed

Augers and progressive cavity pumps are limited to work at a certain extrusion flow. The speed of a progressive cavity pump is between 6.5 RPM and 200 RPM. This is a factor of 30.8.

For example, a progressive cavity pump has its limit at 60 RPM and 14.4 litres an hour before wear will increase significantly, which decreases the factor to 9.2. For both situations, a servo motor needs to be able to deliver this dynamic range of RPM with a gearbox. However, the range of a servo motor could be larger depending on the exact type of servo motor. Table 12.2 and Figure 12.11 compare the theoretical maximum print speeds in relation to the material flow and nozzle diameter of different systems.

12.4.1 Displacement-controlled extruders versus pressure controlled extruders

Displacement-controlled extruders can be controlled by the amount of revolutions. Pressure-controlled extruders cannot be controlled with changing material properties. An auger, however, can improve the results but does not guarantee the control of the volume. Material can stick to the auger and with too little pressure the flow can stop.

12.4.2 Positioning of the extrusion flow control

The material control can take place at the extruder by use of an auger, positive displacement pump, shutter needle or ram extruder, but a hose can also be attached to the nozzle so that the regulation of material is controlled at the material container away from the

Table 12.2 Theoretical extrusion and print speeds

nozzle diameter [mm]	RPM max	l/hour min. RPM	l/hour 60 RPM	l/hour max.	speed min [mm/s]	speed max [mm/s]	speed 60RPM [mm/s]
2	200	1.56	14.4	48	137.93	4244.13	1273.24
3	200	1.56	14.4	48	61.3	1886.28	565.88
4	200	1.56	14.4	48	34.48	1061.03	318.31
5	200	1.56	14.4	48	22.07	679.06	203.72
6	200	1.56	14.4	48	15.33	471.57	141.47
7	200	1.56	14.4	48	11.26	346.46	103.94
8	200	1.56	14.4	48	8.62	265.26	79.58
9	200	1.56	14.4	48	6.81	209.59	62.88
10	200	1.56	14.4	48	5.52	169.77	50.93
15	200	1.56	14.4	48	2.45	75.45	22.64

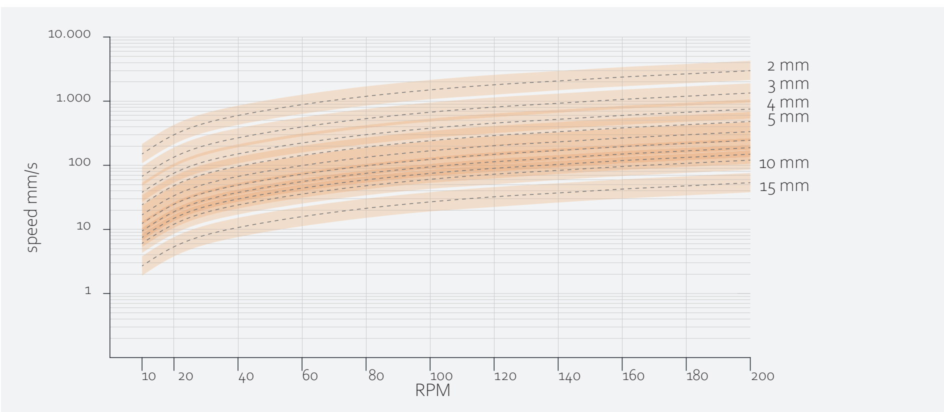

Figure 12.11 Theoretical print speeds, nozzle size, and bandwidth of extruded amount of material compared
The dashed line shows the speed [mm/s] of the tool centre point (TCP) compared to the revolutions of a progressive cavity pump that has a throughput of 14.4 l/h at 60 RPM with a string in which the section area of the extrusion path is 1.5 times the area of the nozzle diameter. The speed of the material in the nozzle is therefore 1.5 times the speed of the TCP. The orange areas in the graph show a bandwidth of the TCP speed whereby the area of the section of the extrusion is between 1 and 2 times the section area of the nozzle.

print head. The advantages of including a hose are:

(1) Light print head
(2) Smaller manipulator
(3) Faster to move
(4) Can be connected to a continuous material feed, which can be controlled separately
(5) Maintenance of parts of the feeding mechanism can take place during the printing process if material feeding is guaranteed in this period of maintenance. This can only be achieved if there is a material surplus between the mechanism and the extruding nozzle for the time period of the maintenance.

But there are also disadvantageous: most hoses expand under pressure. Extrusion on Demand is more difficult to control due to the expansion and relaxation of the hose. The extrusion of material is delayed and after the extrusion stops, material will seep due to relaxation in the hose. This timing difference makes it more difficult to control. The higher the viscosity of the material, the more resistance in the hoses, the more expansion and the more inaccurate extrusion. The more liquid the material, the easier to use a hose between the regulation of the material flow and the nozzle where the material is applied on one another.

It was noted during the preliminary experiments that, when extruding high viscosity material, the flow must be controlled just before extrusion. If the viscosity changes or might change, a displacement control using a positive displacement spindle guarantees that the same amount of material is extruded at all times. An auger will only be able to control the amount by using resistance to start and stop the flow. And the RPM work just between certain values (Cruz, P. J. S., Knaack, U., Figueiredo, B., & de Witte, D., 2017, p. 5), since material can stick to the auger. Cartridge replacement cannot take place without discontinuing the extrusion path by stopping the manipulator. To prevent air inclusion, extra precautions need to be taken to prevent air inclusion in the material and to avoid extrusion of material when “loading” the cylinder in the cartridge. The progressive cavity pump, on the other hand, needs constant inlet pressure, for example, 8 Bar, to prevent fluctuations while extruding. When the pressure drops and the material cannot be pumped, air could be drawn along the gaskets.

The advantage of a mechanically controlled extrusion speed over that controlled by air pressure is that a change in material viscosity does not require the air pressure being adjusted, if present. Positive displacement with the stroke of a mechanical cylinder will theoretically always result in the extrusion of the same amount of material.

The speed and amount of material extruded for the different materials is determined by the viscosity and force applied by extrusion, since in less plastic materials the layers of material can be damaged by the pressure of putting new layers on top of them.

12.5 Flow mechanisms

Extrusion mechanisms differ. Where the piston displacement extrudes the amount of material that travels downwards in the material container, the piston moves by air pressure putting constant pressure on the material. The shutter valve-based extruder stops the flow by cutting of the material flow mechanically, and the progressive cavity pump only extrudes the material when it rotates.

But even though the shutter valve stops the flow, the amount of material extruded within a certain time interval relies on the air pressure applied to the plunger and the material. To control this, not only a pressure sensor to measure the air pressure but also a measurement of the pressure just before the nozzle are required. The high viscosity material and the friction between the material and the material container cause that a full container needs more pressure at the beginning than when it is half empty. To monitor the pressure needed to extrude a certain amount of material in a certain time interval, the applied forces in the material need to be measured for the shutter valve mechanism and the nozzle. Small differences in the materials viscosity will require an adjustment of these parameters.

To extrude thick, highly viscous materials, an adequate technology should be used to prevent fluctuations in the extrusion process. The progressive cavity pump has limitations and will not be able to extrude material mixtures with a very low water ratio. The wear is very high when the pumps are utilised in a continues production facility, especially at higher RPM. However, the pump can be supplied with material through a hose. This is not possible with positive displacement because a hose can expand and relax, causing fluctuations in the material quantities extruded. The selected dosing mechanism is described in Chapter 13.

12.6 Print nozzle

The nozzle is the part of the printer where the material is extruded. Most technologies based on extrusion (§5.1.4) use a nozzle to deposit the material. These vary in thickness, but almost all technologies process the material through a nozzle, where after it is deposited under a ninety degrees angle. When the material is put on top of the built layers, they will spread a little (Figure 12.12). When an extrusion process extrudes lines of material, the ninety degrees angle may damage the material deposited. This could especially happen with materials of higher viscosity.

12.6.1 Material deposition alignment

To reduce the cracks in the lines of clay the nozzle extrudes, the material can be extruded

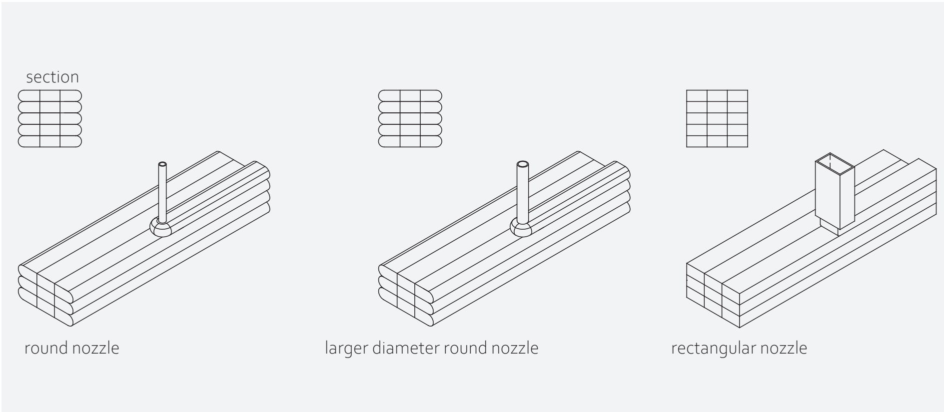

Figure 12.12 Different extrusion nozzle geometries

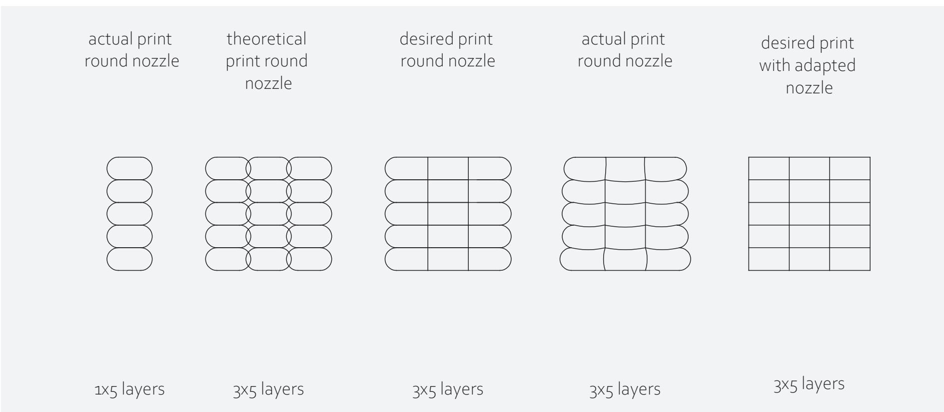

Figure 12.13 Section of extruded paths

at an angle. To follow the path in the corners, the extruder's nozzle should rotate around its own axis. If the TCP is eccentric to the sixth axis of the manipulator, additional movement is required from the manipulator. Compare the different paths of a straight, angled, and eccentric nozzle, and an angled nozzle along the sixth axis in Figure 12.14.

The rotation of the axis is controlled in the code generated to print the part, as well as the kind of material and the amount of material extruded. The controller of the printer can calculate the vector of the movement as well.

This principle of a rotating nozzle has already been demonstrated by Khoshnevis' Contour Crafting (Khoshnevis, B., Bukkapatnam, S., Kwon, H., & Saito, J., 2001, p. 40).

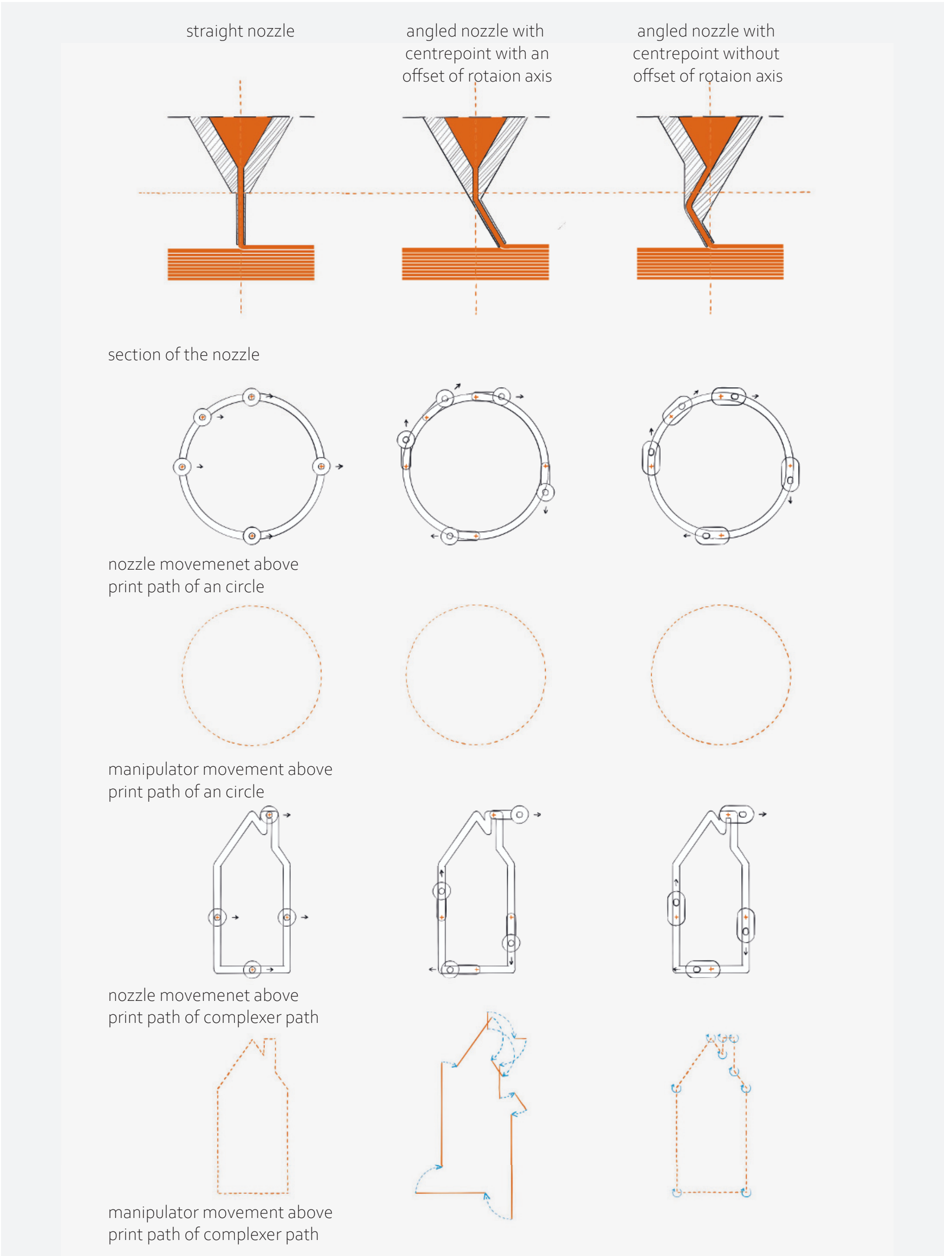

Figure 12.14 Nozzle tip position and manipulator movements

12.6.2 Sensors

Sensors should also be used to control the printing process. To guarantee a continuous flow of material from a progressive cavity pump that is fed by a hose, the pressure at the intake of the progressive cavity pump should be stable. In this case the sensor is used to control the material feed. Although the response of the sensor is quick, a drop in pressure at a material feeding mechanism of a continuous material feeding principle at the end of a hose containing highly viscous material cannot be compensated for within a short period of time. More sensors to predict the pressure at the end and to respond earlier are needed when a hose feeds the material into an extruder equipped with e.g. a progressive cavity pump.

Figure 13.1 Extrusion tool mounted on robotic manipulator

13 Realised AM process for bricks

The realised design in the initiated 3D Brick project (The development of a 3D printing technology and the associated material technologies for the production of innovative structural ceramic bodies using processed raw materials to prototype function- and shape-optimised special brick formats) during this research, of which the possible extrusion mechanism are described in Chapter 12, is a result of the available budget and engineering time and the stakeholder's desires. Due to budget constraints and opinions of project partners, some process designs are not objective.

A schematic printer layout is shown in Figure 13.2. In the project, the choice was made to use a robotic arm with a progressive cavity pump, a small extrusion mechanism on the manipulator, and a separate mechanism that pumps the material to the extruder through a hose (TU Darmstadt & Unipor, 2020). A hydraulic press to realise a large true displacement extrusion technology was considered too expensive and not desirable.

The process layout in Figure 13.2 shows a set-up for a 3D printer based on a robotic arm and tool that can act within a complete production process. The material is mixed, stored to rest and becomes more plastic, where after it is either put in a container (for batch printing) or in a large pug-mill to be mixed and pumped to the extruder.

After the part is printed, the model goes into a drying chamber and is fired and glazed (not shown in the illustration).

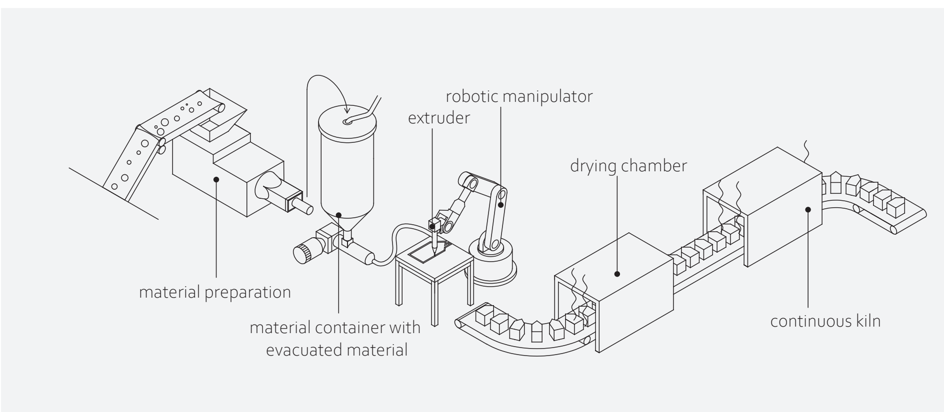

Figure 13.2 Schematic representation of an entire production process with printer

D. de Witte, *Clay Printing*, Mechanik, Werkstoffe und Konstruktion im Bauwesen 62, https://doi.org/10.1007/978-3-658-37161-6_13

Figure 13.3 Material container
Partially filled material container before being closed and evacuated

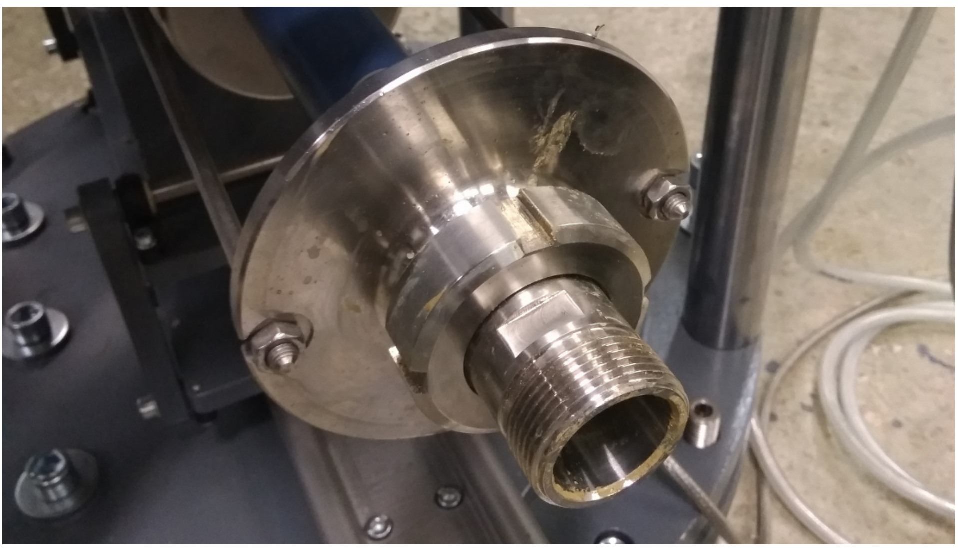

Figure 13.4 Pump of the material container
The pump feeds the extruder material through a hose that is connected to the thread.

13.1 The realised printer for the “3D Brick” project

The robotic arm as manipulator has been chosen because of the high amount of standardisation. The accuracy of the machine is known, and the movement can be controlled by translating a G-code with a CADCAM software in the robot’s language. The research project had a certain empirical basis. The focus was on developing an extrusion technology, expressed by the adaptations of the tool of the robot.

Besides the fact that the robotic arm is a standardised machine, exchange of the manipulator will be easier in future. Within the line-up of machines of one brand, the manipulator (and controller) can be exchanged, maintaining the functionality and offering to scale up the processes if so desired, without additional coding. It will only need a one-time calibration of the manipulator in the complete set-up.

The tool to extrude the clay paste had to be designed specifically to process the highly viscous material and to guarantee the needed dosing accuracy. The mechanisms shown in Chapter 12 could be used to process the clay. Each comes with different properties. In the project, there was the desire for continuous feeding of the nozzle. The realised system, therefore, consists of a decentralised feeding mechanism and a dosing mechanism on the manipulator with a hose in between the two. The extruder was eventually realised as a progressive cavity pump (Figure 13.5) after the resistance of the first extruder accompanying a rotating nozzle was not able to process enough material due to the lack of a pump mechanism (Figure 13.1).

Since the costs and risks within the project were significant, the material feeding mechanism was reduced to a container that could be evacuated (Figure 13.3) and in which a piston applied force on the material, followed by a progressive cavity pump (Figure 13.4) feeding the material through a hose into the extruder and into the nozzle on the manipulator. Thereby the risk regarding the functioning mechanism was reduced, and the feeding mechanism could be replaced by, for example, a small material mixing and extrusion mechanism in the future. The typical mix and extrusion mechanism used in many brick factories will produce too much material to process with this first AM process.

In the project “3D Bricks”, the decision was made to use an additional seventh axis on the robotic arm to control the depositioning amount. The seventh axis is synchronised with the movement and speed of the TCP. The progressive cavity pump in the tool on the manipulator is driven by this seventh axis. Because the progressive cavity pump theoretically delivers a certain controlled amount of material per rotation, the exact amount of material is controlled.

In the research, the controller is realised as a controller with separate IO channels, which eliminates the need for synchronisation between the two controllers. In a later stadium of the ongoing research, more input and output signals could be integrated. Besides that, a machine specific software can be made that integrates all steps (which will be car-

Figure 13.5 Extruder with the 7th axis
The small progressive pump is used for dosing the material just before extrusion. Stator and nozzle are not shown in the image.

ried out manually) before a print, and which may only need a file of a 3D model and a user defined print quality. The complexity of operating the printer will be reduced, but for the preliminary stage of many research projects this kind of investment is not economically feasible or advantageous.

13.2 AM Bricks

After the design has been made, the following steps need to be performed to print bricks with the newly realised printer:

(1) Prepare
- Mixing the material
- Evacuating the mixture to extract the air inclusions
- Loading the material container

(2) Select the settings that determine the print settings such as the tools used and speed
(3) Generate a path based on the 3D model and define the amount of material by slicing the model
(4) Post-processing the raw G-code for the specific printer
(5) Load the code in the printer
(6) Pre-print movements
- Flush the system until there is a steady flow
- Levelling relative to the print bed

(7) Print
(8) Control the print process during the print by verifying the code and by reading sensors and adjusting the movement in real time.
(9) Post-printing movements
(10) Remove model from printer
(11) Post-process and dry the model
(12) Fire

In future, additional steps can be added, for example, glazing and milling of the model. Robocasting has been used to print the first designs of the new bricks. As indicated in Chapter 6, these new bricks benefit from AM as a production technology. Even though extrusion technologies have existed for decades, the challenge was to adapt the material and adjust the process control to improve the process, such that the material dosing over time is controlled.

Figure 13.6 Circular continuous print sample

The accuracy of the print is influenced by:

(1) The precision of the material dosing
(2) The accuracy of the printer
(3) The shrinkage and deformation of the material during drying
(4) The shrinkage during firing

The accuracy of the tool centre point (TCP) is relatively high and will never be off the point-based paths by more than 0.5 mm. The industrial robotic arm is precise in comparison to the desktop printer utilised at the preliminary stage of the research. Since the shrinkage has a large influence, the accuracy is most dependant on the shrinkage and material properties. Post-processing can improve the accuracy of the outer surface if necessary.

Milling can take place between the drying and firing or afterwards, although tooling is more difficult after firing because the material is harder. If the shrinkage factor during firing is known, dried objects can be milled and the shrinkage can be compensated for to obtain the desired geometry after firing. The prints show that the flow is controlled in a better way and that the material has less air inclusions. Figure 13.6 shows a small circular print, generated with the realised printer.

The last chapters described the application and the technology. The performance of the printed bricks indicates the strong and weak points of the engineered printing technology. The printing speed is a parameter that influences the economic feasibility of many products. Even though the costs of building components are important, this parameter is neglected here. If the technology evolves, the production speed generally increases. Ad-

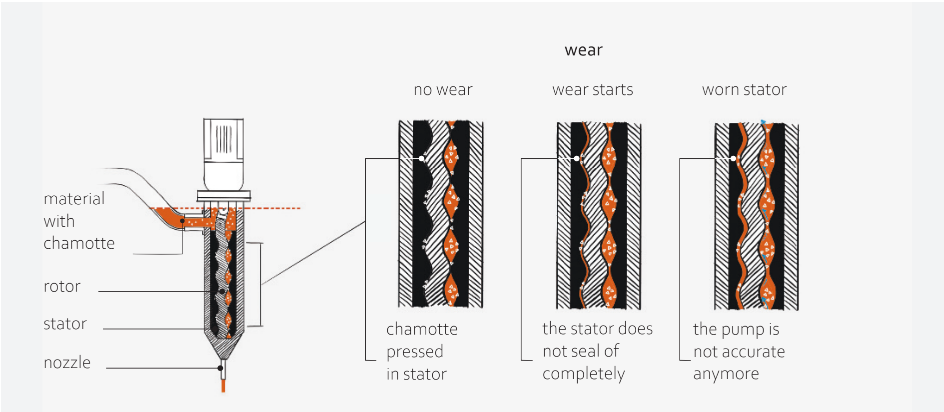

Figure 13.7 Wear in progressive cavity pump

ditional research will be necessary on the improvement of the printing speed, especially since wear increases in the used progressive cavity pumps at higher RPM, as shown in Figure 13.7.

13.3 Process quality

During the first prints, some flaws were observed with the new printer. The material extrusion was not always as desired and it seemed as if the progressive cavity pump for dosing did not process enough material. If the positive displacement pump suffers from wear due to the highly viscous and abrasive material, it will become less accurate after a longer period due to wear of both the stator and the rotor in the system. But with the right maintenance the principle works. However, the material needs to be carefully adapted to the capabilities of the progressive cavity pump.

During the investigation, an additional pressure sensor was mounted at the manipulator's dosing mechanism's material inlet to monitor the inlet pressure and verify the cause of deviations. The high viscosity material causes the progressive cavity pump to not always deposit the same amount of material. This could have had two causes:

(1) Drawing air
(2) Insufficient pressure at the inlet preventing material to come out due to the vacuum in the system above the progressive cavity pump.

The pressure at the inlet of the progressive cavity pump had to be fed with material at a minimum pressure. Fluctuations were inevitable but too high pressures had to be prevented to protect the gaskets in the mechanism. Too low pressure could lead to material

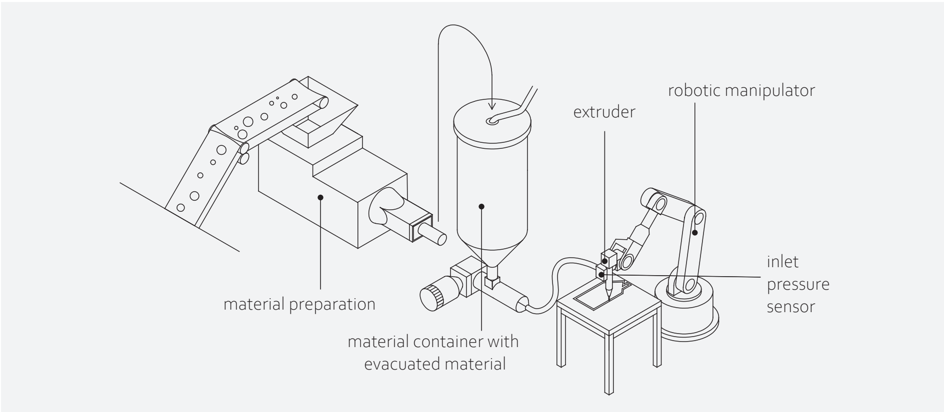

Figure 13.8 Realised printer set up
Schematic representation of the realised printer set-up with a pressure sensor at the extruder inlet

shortage causing the extrusion flow to be interrupted. The material was pumped to the dosing mechanism by use of a larger progressive pump. After the installation of the pressure sensor (Figure 13.8), the RPM was controlled by the input from the pressure sensor. In the system layout used for testing, the pump theoretically reaches a pressure of 40 bar at the outlet of the pump. Inside the hose, the pressure decreases due to resistance. The theoretical amount of material that should be pumped through the hose between the feeding mechanism and the dispensing mechanism was higher than the actual amount of material that came through the hose. This indicates that the progressive cavity pump made more revolutions than was strictly necessary, which could cause additional wear and reduces accuracy.

In some cases, the material coming out of the nozzle was only 10% of the theoretical amount of material. This indicates that the stator and rotor of the larger progressive cavity pump did not seal well enough. The rotor turns and material is pushed against the wall where it flows back in one of the cavities. This was a technical problem rather than a problem of the realised concept.

The theoretical approximately three litres of material an hour that reaches the print head is, however, enough for a print speed of 60 mm per second with a nozzle diameter of 4 mm (50 ml per minute is the equivalent of 3 l an hour). To improve the feeding mechanism, another type of pump could be used with a material expansion cylinder near the dosing mechanism to adjust and control the pressure between the minimum and maximum prescribed inlet pressure, just before the material enters the dosing mechanism which houses the smaller progressive cavity pump.

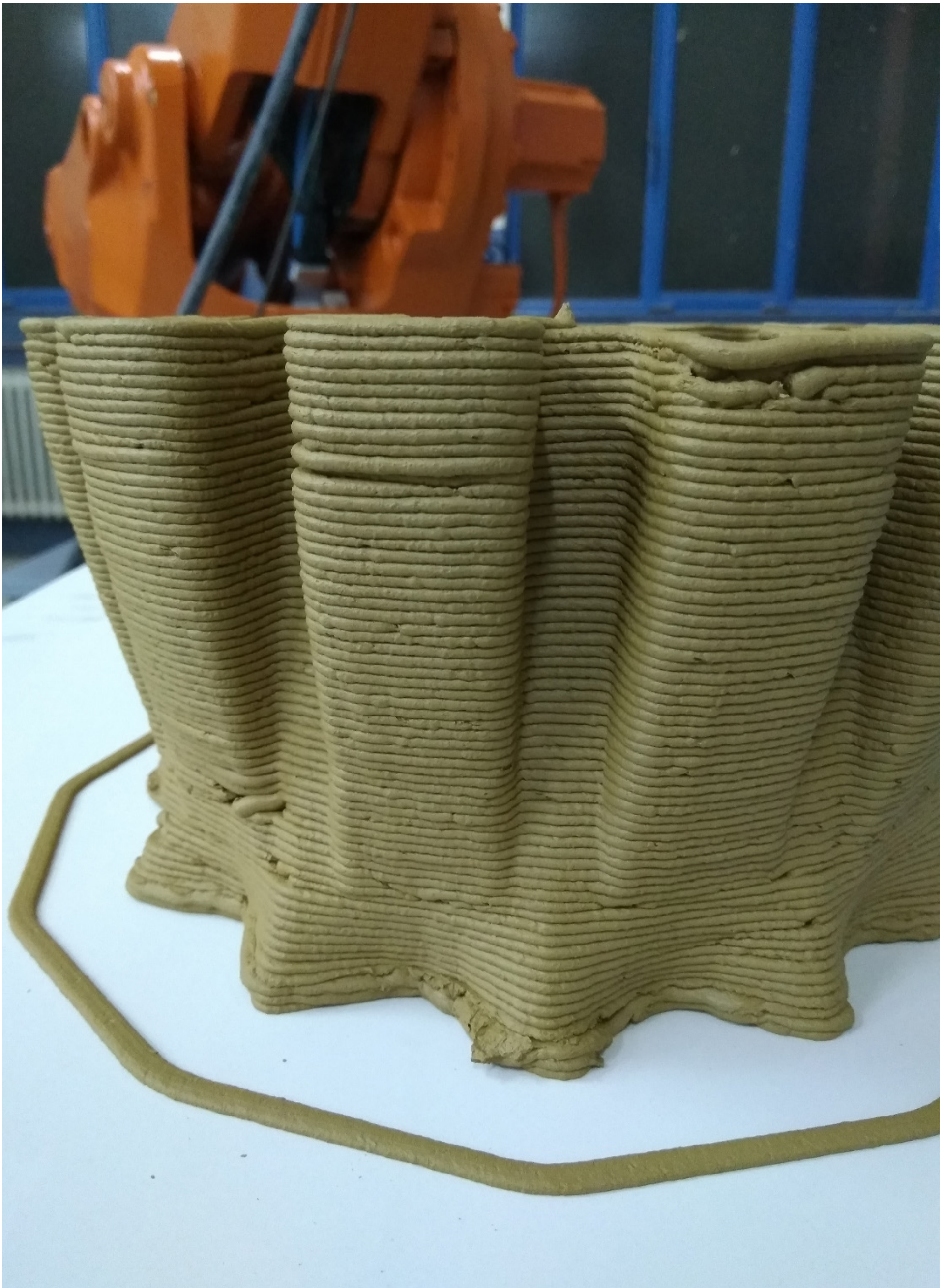

Figure 13.9 First printed free-form with the realised printer
Due to material shortage at the nozzle, some interruptions are visible in the extruded layers.

13.4 Further testing of additively manufactured samples

The print technology improved. Fewer air voids occurred and the accuracy of the path improved, as well. Although the progressive cavity pump's dosing is better, the control of the printer still needs to be improved. Tests with different nozzles should also be carried out.

Proposed is to test and experiment with different extruder nozzle geometries and diameters, all of which in different sizes and at different resolutions. If differences are found, more samples should be tested. More on the proposed tests will be described in Chapter 15: Future vision. However, the extrusion mechanism has to be more stable before that can be done.

Part III

This third part of the research focusses on the evaluation and improvement of the printing process realised.

Figure 14.1 Free-form, glazed roof tiles
Casa Batlló - Barcelona, Spain

14 Evolution

In the fourth generation of brickwork, the aesthetic appearance plays a significant role. To show the potential of the technology, a brick was designed with a geometry that cannot be extruded and is hard to make using (lost) formwork. The bricks were printed and described in Chapter 10.

To print the geometry of the new bricks, a 3D model of the design has to be made. The 3D model is analysed by software and, depending on the geometry, divided in layers or categorised as a surface. If the model cannot be printed as a surface, for which a continuous line could describe the geometry, all individual layers of the geometry will be described by one or more lines. All lines are then translated to a path with additional information regarding the amount of material and desired print speed. This information is sent to the printer. However, these bricks are not yet printed with the new printer; instead, the focus has been on the extrusion quality and on assessing the extrusion principle.

The evaluation describes and evaluates the production process and produced products. The performance and subjects related to improvement are discussed in this chapter.

In Chapter 4, the research questions on "How can silicate ceramic (clay) structural components be produced with an additive manufacturing process to increase the product functionality, and to what extent can they be used in the built environment?" was defined to investigate the potential of AM of clay for the built environment.

The research took care to address all questions in the chapters except those that involve a future vision. It can be concluded that robocasting showed to be a reliable production method that can process adapted clay ceramics with a lower viscosity than the material used in the brick industries' automated processes, although the newly designed extrusion mechanism had some flaws which need to be improved.

The products that benefit from this technology are individualised free-form products that cannot be made with traditional processes, or are requested in very small batch sizes. The small batch size is beneficial because AM does not require a die or formwork. Examples that could be printed are aesthetic components such as individualised lintels, corner bricks, but also high performance parts that could improve building physics.

After producing bricks with traditional technologies for centuries and improving the material and products performances, AM of ceramic building components is the most recent development. Although AM can be seen as a disruptive technology to process clays regarding form, batch sizes, internal geometries and the ability to mix materials in one product, the material itself has to be prepared for robocasting as for traditional processes. The exact material mixture differs, but the need to store the material and enhance the material properties over time – related to an increased plasticity before processing – to

D. de Witte, *Clay Printing*, Mechanik, Werkstoffe und Konstruktion im Bauwesen 62, https://doi.org/10.1007/978-3-658-37161-6_14

generate a material that functions well without high water content, is similar to the traditional material preparation for bricks.

14.1 State of the art redefined

History shows that the processes utilised for traditional brick production are based on the material characteristics. The new AM technology showed that it is able to process clay, but additional conditions derived by the fact that the clay body is produced in layers needs need to be taken into account. The extrusion process needs to be controlled the same as with traditional extrusion processes; however, for AM it is important that the extrusion speed is exactly synchronised with the length and curvature of the print path. This is important because in a movement, described by a path, a surface needs to be covered with an exact amount of material. Extrusion fluctuations cannot be corrected for during or after the print. Besides these challenges, the printed parts showed a lot of potential.

14.2 Print technology

The typical conditions of the building industry demand, are a specific processing principle that provides a technology for free-form processing of classic clay material at an affordable price. This involves:

(1) A relatively high-speed processing of the material
(2) A good accuracy provided by green strength or support material
(3) A good compactness of the material
(4) An uniform distribution of the material
(5) A good surface quality
(6) The possibility to process classic clay materials like terracotta and stoneware

To process a traditional clay such as terracotta or stoneware, the characteristics of the seven processing principles defined in ISO/ASTM 52900 have been compared to the conditions needed to print the desired products types. While there were multiple processes that could fulfil the conditions regarding speed and accuracy, the determining condition are related to the desired uniform material distribution, like the clay materials with aggregates and the desire to print dense materials at a reasonable speed. Up-scaling a powder bed in size and not operating it at 100% capacity costs time, because every layer needs to be created, even for the part of the print bed that is not used. The robocasting technology has advantageous and disadvantageous properties but has shown its potential in this research. The advantage of the extrusion of high viscosity clay paste is the high compactness of the green body and the ability to process larger aggregates. One disadvantage is

Table 14.1 Characteristics of robocasting

advantages	disadvantages
dense material	no support material
fast material depositioning	lower resolution
can process normal clay ceramics	no large aggregates between the layers
use of aggregates	

the layering method, because it prevents larger aggregates between the layers.

In the comparison made in Chapter 8, the weighted arithmetic mean of the extrusion-based technology was the best. The technology of robocasting was selected for clay extrusion because it can extrude the material paste and because robocasting scores best on the conditions defined to print the desired designs. The printing speed with one nozzle can be fast due to the amount of material that can be deposited if a nozzle with a relatively large diameter is used. Post-processing can improve the surface quality if a technology scored low in this aspect.

In traditional processes, the high viscosity clay mixture is processed after mixing and curing. The mixing and curing required to obtain the desired material properties, however, needs time and when working with powders in a AM principle (e.g. binder jetting or laser sintering) this cannot take place to the same extent. The internal geometry cannot be completely post-processed in all cases. The resolution stays as it was when printed. As long as the external geometry is the only visible and important surface for the performance of the brick, the rough inside can be accepted. When advanced geometries use the internal geometry for internal piping, for example, this geometry may need to be post-processed during the print to make sure the surfaces are still accessible for post-processing. This will introduce new challenges regarding post-processing since post-processing fresh, wet material, is more difficult. Like the process, the post-process tooling can be adapted to better process complex internal geometries, as well.

Traditional brickwork factories use auger-based pumping mechanisms. These systems cannot guarantee to extrude the same material with a changing viscosity. For AM it is harder to compensate for such a fluctuation in material. The amount of extruded material has to be the exact amount of material in the exact time over the predefined path. A surplus of material due to a lower material viscosity cannot be compensated for and will result in thicker or wider layers of extruded material. To minimise this effect and to cope with fluctuating materials, a progressive cavity pump has been used in the “3D Brick” project. The progressive cavity pump can theoretically extrude materials with a high accuracy but there are limitations. This is caused by the RPM and output pressure in relation to introduced heat which could dehydrate the material and cause internal wear of the progressive cavity pumping mechanism.

In the testing period, however, the viscosity of the desired material mixture seemed to be fluctuating and slightly too high, causing the first pump to inconsistently feed the second pump in the system with a sufficient amount of material. To compensate for this issue, the resistance had to be lowered by making the material less viscous. The progressive cavity pump is a good tool to extrude the material but seemed to have its limitations for clay processing and components will wear over time. It will be challenging to adapt the systems to be precise for a long period of time. Pre-print calibration of the system can, however, be used for monitoring and control. A line, for example, could be printed and weighted to calibrate the printer. The viscosity can be determined, as well, and function as input to control the extrusion process.

14.3 Material

The silicate ceramic material used for printing is a natural material, and material fluctuations occurred between different batches. Therefore, in the production process, the ability to process a variety and fluctuating mixture of materials is an important condition for printing clay. Traditional processing technologies such as industrial extruders can compensate for a change in viscosity after extrusion when the bricks are cut. The length is determined by the cutting process and will stay the same although the material's viscosity changes.

By using an extrusion technology that is based on progressive displacement of the material within the system or pump, the material flow can be controlled, as well, and a variety of materials can be processed because the viscosity is less influential. However, there are boundaries. The material mixture needs to remain between boundaries and fulfil certain conditions regarding plasticity and green strength. The materials used in this research had a resulting height of approximately 10 mm after the Pfefferkorn test. More research needs to be carried out to process other materials.

14.4 Printed parts

AM of clays has potential, shown by the first additively manufactured bricks with a freeform geometry. Certain overhangs could be printed without a support structure. The new printer had some flaws but also featured very good continuous path extrusion compared to the desktop printer used in the preliminary research. The resolution of the printed parts depends on the nozzle used in relation to the selected width of the path. Overhangs depend on the green strength of the material and the thickness of the path and connection to the layer underneath. The final surface quality is influenced by post-processing as well.

14.5 Performance

In the research, first tests were carried out regarding performance. A distinction was made between aesthetic performance and structural performance. The aesthetic performance is determined by the resolution and continuity of the extrusion flow as well as the variety of material. It was carried out for products printed with the desktop apparatus.

Just like the aesthetic performance, structural performance was influenced by many parameters. The parameters below relate to the material, print process, slicing, and post-processing:

(1) Material composition
(2) Water content
(3) Homogeneity of the material mixture
(4) Uniformity of the material (e.g. amount and size of air pockets)
(5) Resolution
(6) Direction of the printed lines in relation to the applied force
(7) The firing temperatures and degree of vitrification

It can be concluded that the selected robocasting technology showed to be capable of printing the first free-form geometries with a terra cotta and stoneware material; however, the technology can be improved. To improve and gather more knowledge on the printing technology, the parameters mentioned above are a starting point to experiment with. The next chapter will provide information on further research.

Figure 15.1 Brickwork buildings from different time periods
Hotel New York and Montevideo, Kop van Zuid, Rotterdam, The Netherlands

15 Future vision

The possibilities and challenges of AM of silicate ceramics (clay) for the built environment have been discussed. The research shows a broad overview of printing silicate ceramics, but further research needs to be carried out. To improve and derive additional knowledge based on this research, new research can provide information on these subjects.

Improvements can be done on an empirical basis, to improve the results, searching for a better performance of the product or to initiate improvements based on regulations after the preliminary experience with printing bricks. For technology improvement and utilisation within the built environment, it is necessary to continue the research.

It has been shown that building parts can be printed. It is important to define the boundary conditions of brickwork to be safely used within the built environment. The standard norms describe structural performances, processing methods, and testing methods for traditional brickwork. The testing methods are based on testing produced bricks. This is difficult to do for additively manufactured bricks, because they are not produced in large batches. New research could, for example, focus on how certification could be adapted to the different production processes. To do this, it is important to define how additively manufactured bricks can be certified. Once this is specified, the process can be adapted by using the input from the certification process to fulfil the requirements.

The future vision discusses the subjects and fields that should be investigated further. Based on a roadmap, several topics are placed in the context of future research. The advanced brick with integrated functions shown in the first part of the research has not been printed yet. The print process has yet to evolve to facilitate this, and therefore the idea of a heat exchanging brick together with the aim of certification are used to describe future research topics.

15.1 Future products

Future products that can be envisioned are related to free-form, integrated functions, and optimised structural performance. Depending on the speed of the print process and the economical feasibility, the type of products that can be made by utilising AM for clay building components is endless. This research has tried to realise a printing process that is capable of processing multiple materials, to have a high level of freedom regarding the adjustment of surfaces that can be printed on, and allows for different resolutions that can be achieved by interchanging nozzles. Products with special internal geometries are challenging, but they can provide special functions that cannot be made with traditional

D. de Witte, *Clay Printing*, Mechanik, Werkstoffe und Konstruktion im
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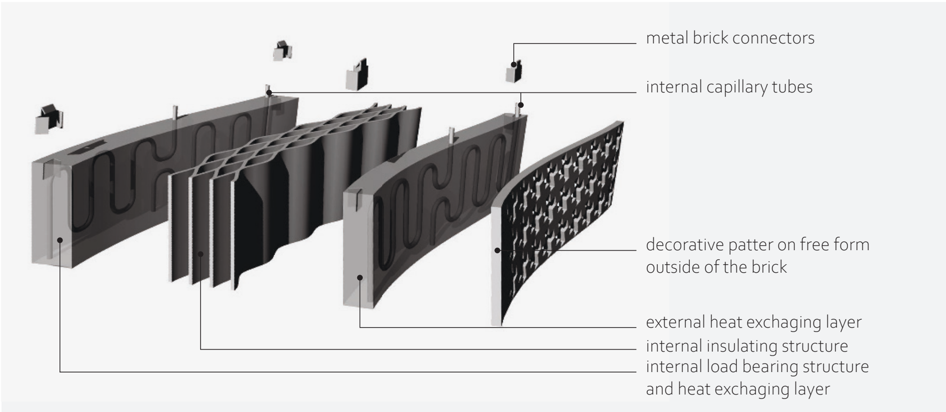

Figure 15.2 Heat exchanging brick

production technologies. Free-form products can also be printed to further the field of refurbishment and newly designed buildings. Combinations of ornamental products with integrated functions are possible, as well. Examples are free-form cladding elements or load-bearing monolithic brick components with embedded piping to function as a heat exchanger on a building as described as an advanced product in Chapter 1. Even though the heat exchanging brick (Figure 15.2) has not been printed yet with robocasting, it is a design that can be used to assess improvements of the technology in the future.

15.2 Roadmap

The roadmap shows a future vision of how AM of clay-based ceramics could evolve. The new research topics are listed according to the process sketched in Figure 15.3. The subjects can be categorised based on the motivation. They can be based on the preferences to improve the quality in general, pushed by certification or by industrial improvements of related industries.

Since the goal is to implement the process in the built environment, the list of potential future research starts with research for certification. The roadmap shows a circle; which highlights the fact that starting with certification is important, because improvements regarding certification could affect the type of improvements in the production technology. Besides certification, the other motivations for improvement are general improvements:

(1) Additive Manufacturing
- Extrusion accuracy
- Ability to print cantilevers
- Hardware

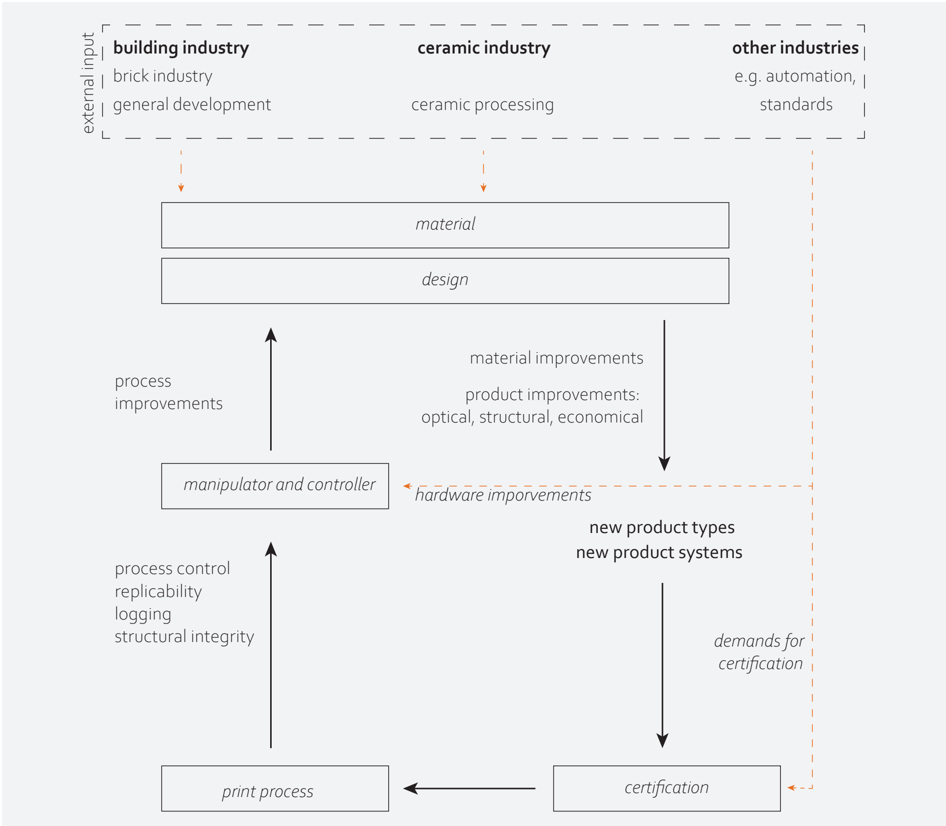

Figure 15.3 Roadmap future research

- Software

(2) Structural performance
- Layer connection
- Print angle and direction

(3) Optical performance
- Accuracy
- Surface quality

(4) Material improvement

(5) Products
- Print on standardised products

External input different industries:

(1) Complete production chain
(2) Automation improvements of the process

15.2.1 Certification

Since the geometry is highly individualised or the elements are produced in small batches, it is practical to certify a process instead of the product to benefit most of the printing technology. To investigate if process certification can result in accurate quality predictions, test samples have to be printed to obtain information on the most influencing parameters that should be monitored. The method of certifying glass is an option for AM. Further research on this topic is needed. Can quality control be based on process monitoring? What data needs to be collected for adequate process monitoring? If this subject is investigated, the printing process can be adapted and a protocol for adequate logging can be established. To investigate the influence of the production process on the printed products, sensors and logging can be implemented in the machine (Figure 15.4).

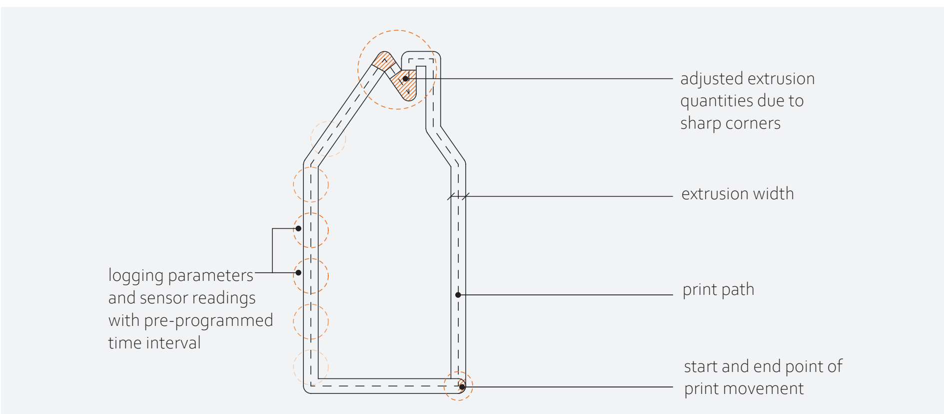

Figure 15.4 Improvements: replicability, logging, and corner accuracy

Figure 15.5 Will future columns have bone structures?
Rendered image of a slice of a column with a complex inner geometry and capillary piping.
Source: de Witte, D. (2015)

15.2.2 Future research topics

Certification is part of the implementation of the additively manufactured clay products within the built environment. To improve the technology to facilitate the implementation of the brick components in the built environment, it is important to investigate how additively manufactured clay parts can be certified. The topics related to certification and improvement of the printing technology and their correlation to different research subjects are shown in table 15.1. Every topic is categorised and provided with an accompanying description.

Table 15.1 New research ideas

categorised subjects	certification	design	print process	manipulator and controller	material	description of research topic
certification						
how can additively manufactured silicate ceramic (clay) parts be certified	■					Research on how certification can be obtained for additively manufactured silicate ceramic structural building components.
design	■	■	■	■	■	
new (internal) geometries	■	■				Further research on what forms benefit most if printed. A comparison of costs of moulding and other technologies and a LCA of them to investigate the impact of AM.
high performance bricks regarding building physics/ structural strength / performance		■				The introduction mentions small pipes inside the printed bricks. These bricks have not been printed yet. Therefore, the performance is unknown and should be investigated. The higher performance bricks can be developed to obtain better performance regarding building physics, e.g. insulation or sound insulation.
post-processing steps		■	■			Post-processing steps such as milling and glazing the 3D printed brickwork products could be achieved. E.g. milling can take place after the printed object has been scanned. After the geometry is precisely made the component can be painted or glazed by another tool on the manipulator. The ceramic will be fired where after the bricks can be shipped to the building site. However before transport the bricks can also be stacked either with or without standardised bricks into a prefab element which is shipped to the building site. The research should focus on which post-processing method can be used for silicate ceramics (clays) after they are printed.

Continuation of **table 15.1**

categorised subjects	related categories: certification	design	print process	manipulator and controller	material	description of research topic
print process						
how does the dosing mechanism based on a progressive cavity pump function over time?		■	■			Can the silicate ceramic material be extruded with a progressive cavity pump over a longer period of time and when do stators need to be renewed to facilitate an accurate dosing. Does the dosing mechanism need additional sensors to compensate for wear?
nozzle diameter	■		■	■	■	The nozzle diameter where through the clay is extruded can have different diameters. The diameter of the nozzle and the amount of material extruded during a predefined path, determines together with the layer height the width of the extruded material. While it is unclear whether the diameter of the nozzle influences the accuracy and the bond between the layers. This has to be analysed.
extrusion speed	■	■	■			To implement AM within the traditional production process of mixing, shaping, drying and firing is possible, but to process many objects a higher speed is desirable. By up-scaling and using multiple robotic arms to print, more products can be made. However, it is interesting to analyse and improve the production process to increase the extrusion speed, in order to increase the overall printing speed.
layer connection	■	■	■			What is the influence of the printing technology, the used nozzle and the print path on the layer connection?
multi-material		■	■	■	■	While there is a variety of different clay mixtures, it is interesting to investigate in further research if multiple materials can be printed. It is important that the different clay mixtures share material characteristics to prevent high internal stresses during and after printing. Also should be investigated how multi-material printing can be integrated in the printing process.
printing support structures	■	■	■			How can support structures be realised and is an additional support material preferred?
rotating nozzle	■	■	■	■	■	Can the product characteristics and material deposition be improved by use of a rotating nozzle? How is additional rotation implemented in the G-code?

Continuation of **table 15.1**

categorised subjects	certification	design	print process	manipulator and controller	material	description of research topic
manipulator and controller						
print bed geometry and material			■		■	Which material is best as print bed? This subject could be examined in combination with a material research. Could the print bed's form be adjustable and how could the print bed improve print qualities?
print on semi-finished products	■	■		■		Is it possible to print on semi-finished products? What characteristics should the manipulator have and what conditions should the semi-finished and print material have?
modular temporary formwork			■	■	■	Can temporary formwork be used when printing silicate ceramics? How can this be integrated into the print process?
process integration in factory		■	■	■		Robotics can be utilised for many applications. Most robots in within brickwork factories are used to pick and place or palletise bricks. However robots can be used for additional steps within the production process. After printing what post-processing steps that could be carried out and do these steps allow for new possibilities?
automation PLC and sensors, g-code and control of the printer	■	■		■		Related research topics are on the movement of the printer and the communication of the model to the machine by help of a specific code (G-codes). Should there be a G-code type which has more information embedded in it? Should the machine have it is own code language? These questions depend on how the machine is used. Within a company it could be both. For a printer that could be used by many firms and universities a universal code would be logical. However, in both cases, what information should this code contain? Besides the certification and process improvements based on demands of the brick and building industry, input from other disciplines can help to improve the process and product (systems) made. Sensoric and automation based on the read out of sensors could help certification.

Continuation of **table 15.1**

categorised subjects	related categories: certification	design	print process	manipulator and controller	material	description of research topic
material						
firing temperatures and its influence on the product characteristics			■		■	Firing temperature has an influence on the silicate ceramic (clay). The influence on the performance of firing temperatures on the adapted material mixtures has to be examined. A subdivision can be made on: shrinkage (aesthetics), building physics, and strength (structural performance).
influence of the direction in which the material is applicated and the height of the individual layers	■	■	■	■	■	It is important to know the influence of the material on the print process and the influence regarding application direction and layer height on the final products.
layer connection strength and spread of material	■	■			■	The connection between the layers seemed to influence the strength of the printed part while the structural strength test showed that there was a difference in performance when the tested beams print direction was along the applied force or perpendicular to the applied force. The anisotropy is demonstrated by the compressive and bending test in Chapter 10. Additional research into this phenomena has to be carried out. Especially for the certification of the products.
how to reduce the influence of shrinkage			■	■	■	To what extent can the material be changed to reduce shrinkage but preserve the needed plasticity for the printing process?
material mixture	■				■	The material processed was a earthenware and stoneware material. This to stay close to the terracotta brick material widely used in Germany. There are other materials with beneficial properties for the printing process. Because the material is used for special forms and not to mimic standard bricks, a more expensive material can be used. This material could consist additives that will never be economical in highly standardised, mass produced, bricks. A future research topic could focus on the application of different ceramic types.

15.3 Expectations

The research showed a broad overview of printing silicate ceramics, the first printed bricks, the performance of samples, and the roadmap accompanied by the table with future research topics. It also showed that research on the printing of silicate ceramic building components is not completed.

While the machinery was not available yet, a printing mechanism has been described and the realised printer has been shown. This provides a starting point to improve future machinery, but also allows for simultaneous research on the printed parts. One example of the questions still needing to be investigating is whether printed organic forms can be certified and implemented in our built environment. The extent of freedom in form will be determined by regulations and production processes.

The building industry has to be innovative, and buildings are not produced in large batch sizes. Therefore, it is at least expected that the utilisation of printed silicate ceramic parts will take place during the initiated elaborating research on this topic for the field of architecture and building technology.

Figure A.3 Witte huis
Rotterdam, the Netherlands

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All schematic line drawings are made by the author. Drawings 5.3-5.9, 5.13, 8.10, 9.2, 9.3, 12.2, 12.4, 12.10, 12.14 and 13.7 are made by the author and edited/redrawn by L. Lauwerends. Sources, if applicable, are indicated below the diagram.
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