New Tools for Ceramic Extrusion: Developing Craft Experiments into Industrial Applications

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Abstract

This paper covers ongoing research into profile extrusion with ceramics and how new digital technologies can be used to facilitate innovation with the process, particularly focusing on tool making scenarios with the extrusion profiles (dies). The research was initiated as creative explorations within the author's own craft practice, however the project has since developed into a UKRI funded project with multinational companies collaborating as research partners. The paper will provide a brief historical context of ceramic extrusion with coverage of the process in both the architectural ceramic industry and the craft sector. The paper will then outline the author's creative experiments with the method and the use of 3D printing as the key technology for creating the extrusion dies. The paper will then describe developments in terms of transferring the knowledge from these experiments into potential applications in the architectural ceramic industry.

The research has exposed challenges to expand the use of extrusion in terms of the availability of key equipment, such as extruding pugmills. In response to this situation, and as an integral part of the research project, a concept for a low-cost hydraulic extruding system has been developed, which will also be covered in this paper. This paper will conclude by the author providing reflections on how craft research has the potential to deliver innovation beyond its own disciplinary boundaries.

Keywords

Ceramic Extrusion, Craft Practice, Innovation, Tool Making, Architectural Ceramic Industry, 3D Printing, Digital Fabrication, Technological Indeterminism, Jugstrusions.

Introduction

The principle of using extrusion to form clay into products can be traced back to the early 17th century with the first known example being a piston extruder developed for the production of bricks. Later in that century, extrusion machinery for the productions of tobacco pipes was developed in Amsterdam (Händle 2007, 92). However, these examples constitute somewhat isolated cases of the use of the process and it was not until the mid 19th century that extrusion began to be used much more widely, especially for the production of architectural components (Händle 2007, 100–108). Into the 20th century clay extrusion became increasingly utilised as an efficient production methods for manufacturing bricks, water pipes and tiles. While a number of improvements of the process has gradually been introduced, the core principle of the process has remained largely unchanged with two basic principles utilised; piston and auger. The piston principle is based on the use of a ram to force clay located within a tube through a profile located at the end of the tube. In contrast, the auger principle is based on the use of Archimedean screw(s) to propel the clay through a chamber and force it through a profile. The auger principle requires significantly higher levels of engineering but the principle has the capacity to provide a continuous flow of output, and therefore has far greater potential in industrial production scenarios. Consequently, the method has been widely adopted by architectural ceramic industry as a highly efficient production method for the mass production of building components. However, ceramic extrusion has also been utilized for much more refined products, with a notable example being the production of filters for catalytic converters (Beall and Cutler 2020). While there have been some optimization and automation in the use of the extrusion method in the ceramic industry, more significant innovation with this production technique has been limited and many of the industrial setups have remained unchained for several decades.

The use of extrusion has also long been utilised in the craft pottery sector. In this field extrusion has primarily been used as a supporting making technique to produce handles and other minor elements with manual hand operated extruders based on the piston principle being commonly utilised for this purpose. Despite such extruders being widely used, the process has been largely overlooked as a primary production tool, with only one publication Pancioli (2000) dedicated to the subject. However, there are still a few notable examples of individual ceramic practitioners that have explored the technique with some more innovative approaches, including: Floris Wubben (Studio Floris Wubben 2018), Max Cheprack (Hîrdo 2012) and Anton Alvarez (Alverez 2019). Beyond individual practitioners there are some examples of some larger ceramic studios also using the process as the central method for the production of pieces. These include Tommerup Ceramic Work Centre in Denmark, which have utilised their semi-industrial extruder as the main manufacturing tool in many of their large scale ceramic art projects (Jakobsen and Mikkelsen 2018). Liverpool based, Granby Workshop, has also utilised the extrusion process creatively with the 2017 A Factory As It Might Be installation as a particularly noteworthy project (Assemble 2017). Studio Apparatu, in Barcelona, has also provided examples of how the extrusion process can be effectively used beyond the conventional applications, with inspirational furniture and interior designs (Apparatu 2020).

These examples provide evidence of the potential that profile extrusion presents. However, the author firmly believes that there is significant underutilised innovation potential with the method, particularly when combined with new digital design and fabrication technologies. The aim of this research is to provide knowledge which can enable far greater utilisation of ceramic extrusion and to highlight the significant creative and commercial opportunities the process presents.

The Use of Digital Design and Fabrication Technologies in Ceramic Production

Innovation with digital design and fabrication tools in the field of ceramics has to date been predominantly focused on 3D printing with both powder and plastic clay based methods having been established. In regard to 3D printing with plastic clay it is worth highlighting that this method also involves the use of extrusion. However, in this process extrusion is a part of the mechanism of the print head that delivers the ceramic paste within an Additive Layer Manufacturing (ALM) principle, which 3D printing is based on. This use of the extrusion principle in this context is fundamentally different from profile extrusion, which this research is focussed on exploring. ALM methods have presented ceramic practice with opportunities for exploring new aesthetic possibilities, and the use of 3D printing with plastic clay in particular has gained significant use over the last five years, pioneered by the work of Studio Unfold (2020), Jonathan Keep (2020) and Olivier Van Herpt (2018). However, 3D printing remains a slow production method compared with traditional craft based making methods such as throwing or press moulding.

In terms of the ceramic industry, the use of digital tools has to date been patchy. Computer Aided Design (CAD) tools have long been used in the sector, with software programs specifically developed for the sector such as PlateScribe and DeskArtes introduced almost three decades ago. Some computer-controlled milling and 3D printing have been utilised in bigger industrial ceramic companies including Wedgwood and Denby Potteries, but used almost exclusively for visualising new design proposals rather than in applications within the actual production.

Overall, apart from 3D printing with plastic clay, the emergence of digital fabrication tools appears to have had relatively little impact in terms of expanding innovation opportunities with ceramic production – both within the industrial and craft sector.

Craft-Based Experiments with Ceramic Extrusion and 3D Printed Dies

The author's interest in the concept of using 3D printing for the production of extrusion dies began in 2016, when being induced to the approach by ceramic artist Taslim Martin. Martin had conducted a series of small-scale experiments with 3D printed dies for the use with a brick motor gun as the extrusion mechanism. The author recognised 3D printing's capacity for creating complex geometric forms as a significant innovation opportunity for new approaches with the extrusion process. In particular the possibility of exploring new creative potential in process by creating dies which could generate curved extruded forms.

Fig 1: 3D Printed Extrusion Dies by Taslim Martin, with extruded clay form on the right. Images: T. Martin 2016

The author started to undertake experiments to establish if the concept could be developed for use on an increased scale. The experiments were focussed on creating extrusion dies with a teardrop profile with the aim of developing a concept for extruding jug shapes from dies that would generate a curved shape that would enable pouring capabilities. For these tests a manual extruder with screw operated piston was employed with a customised 'expansion box' that enabled larger scale dies to be use beyond that of the diameter of the piston cylinder.

Fig 2: Screw action piston extruder used for the initial tests undertaken by the author, the expansion box that facilitates larger diameter die is illustrated in the image to the right. Photos: T. Jorgensen, 2016.

The dies were fabricated on low-cost MakerBot 3D printers which work via the Fused Deposition Modelling (FDM) principle through the use of plastic filament as the build medium. For the dies in these initial experiments ABS plastic filament was employed. The initial results were not encouraging with the dies consistently being crushed by the extrusion pressure. In this regard it is relevant to note that FDM 3D printing typically creates parts that consist of a solid outer skin but have an interior that is printed with a loose three-dimensional mesh, known as infill. This infill typically only constitutes 10-30% of the volume of the interior space of the parts. The reason for this approach is to minimise printing time and also to reduce material use and cost of the parts. FDM 3D printed parts are very rarely printed with a solid infill due to excessive printing times such an approach would result in.

Fig 3: Failed 3D printed dies due to the extrusion pressure, with the characteristic sparse interior infill revealed. Photo: T. Jorgensen, 2016.

In the efforts to resolve the failures of the initial dies, the sparsely filled interior of the 3D printed dies was identified as just one of the issues coursing the dies to fail. The layered nature of 3D printing parts was also identified as a significant aspect in the structural weaknesses in the dies, resulting in delamination along the horizontal layers. Particularly the supporting beams, known as bridges, which hold the central core of the die in place seemed particularly woundable in regard to this aspect. In response to these issues a hybrid construction approach was adapted where 3D printed parts were combined with metal bars inserted to form the bridge components of the die design. The 3D printed dies parts were specifically designed with slots to incorporate not only bars but also holes for bolts to brace the die to prevent de-laminating along the 3D printed layers. This approach proved to be successful in alleviating the structural failures of the dies.

To aid the design iterations the authors developed a parametric script in Grasshopper – the visual programming environment within the Rhino 3D CAD software. This Grasshopper script (which is also known as a definition) enabled the author to iterate particular elements of the die design while other parts would update automatically in relation to the alterations.

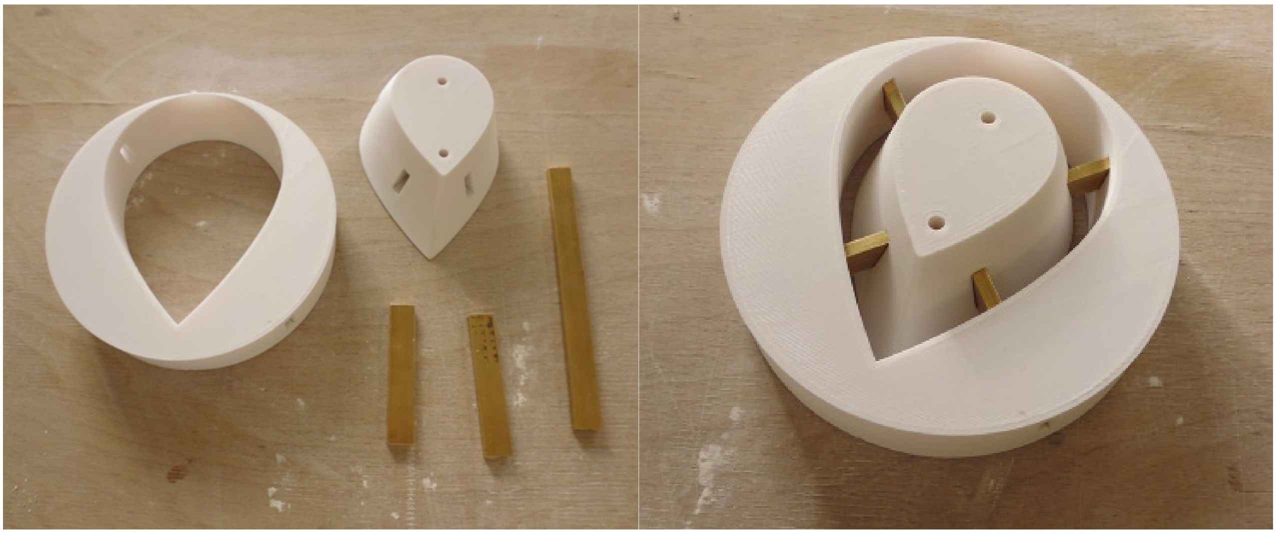

Fig 4: 3D printed die with slots to incorporate brass bars to operate as bridges to hold the core. Photos: T. Jorgensen, 2016.

As previously highlighted the overall aim with this investigation was to develop dies that could create jugs through the use of a single profile clay extrusion. The concept was envisioned to be achieved through particular geometries of dies, which would force the clay to curve on exiting the die – and thereby enable pouring capabilities of the extruded shapes. The almost limitless geometric freedoms that manufacturing via 3D printing presents, meant this production technology was considered to be an ideal way of achieving this concept. However, the complex rheology that governs the physics of clay extrusion presented the author with some surprises in this regard. Initial experiments with the dies resulted in jugs that curved strongly – but completely in opposite orientation that was intended with the point of the pouring lib bending back rather than forward. As the experiments continued, and with the author implementing design iteration of the die designs more promising results where the extruded form curveed (broadly) in the intended direction, were achieved.

While succeeding with the basic principle of this new jug making concept, several other challenges in creating a production workflow also had to be addressed. In particular the handling of the soft extruded shapes proved difficult and approaches for rapid drying and hardening of the shapes had to be developed. This was addressed through the use of upholstery foam to rest the jugs on, as well as the use of fan assisted hot air dryers. The trimming of the tops and based of the extruded jusg proved challenging and required a honing of the author's hand skills and the creation of the bases for the jugs required the development of a new working procedure. This procedure involves placing the trimmed jugs on a dry plaster bat and then carefully administering liquid clay (casting slip) via a syringe fitted with a plastic tube in the enclosed area created by the perimeters of the jug base. In this process the plaster absorbs the water from the casting slip to create flat bases for the jugs.

Fig 5: Images illustrating part of the workflow for creating the Jugs. Extruded shapes resting on foam pieces to harden (top left image), scraps from the trimming process is illustrated in bottom left image, and jugs placed on plaster bats to form the bases is illustrated on the image to the right. Photos: T. Jorgensen, 2016.

Through a period of creative experimentation with the process, the author observed that the rheology involved with the extrusion process would course unpredictable outcomes and the process seem result in an inherent variability in the shape of the jugs. Identical setups with a particular die and clay of the same batch and hardness would often result in significantly different curved jugs. Reflecting on this finding the author sought to embrace the variability in the output as a potentially valuable aspect in artefacts that would be aimed for the craft sector market. Arguably, this is a sector where uniqueness of artefacts is not only accepted, but generally valued. Through these observations, the author proposes the creation of new term: Technological Indeterminism. This term proposes an approach where new digital fabrication technologies (in combination with particular material characteristics) are used to create novel making process that have significant levels of unpredictability and where the results are inherently unique, see full definitions in figure 6:

Technological indeterminism

jtek-n*uh*-**loj**-i-k*uh*l-in-dih-**tur**-m*uh*-niz-*uh*m
noun
noun: **technological indeterminism**

1 The use of advanced digital fabrication technologies to create tools or manufacturing processes which though the use of particular manufacturing mediums creates outputs that cannot be fully determined and thus have unpredictable and interesting qualities.

Word constructed from:

- Technological (adjective): of or relating to technology; relating to science and industry.
- Indeterminism (noun):
  - The doctrine that not all events are wholly determined by antecedent causes
  - The state of being uncertain or undecided, the branch of knowledge dealing with engineering or applied sciences.

Fig 6: Description of the new term; Technological Indeterminism, proposed by the author.

Another term which the author proposes as a result of the development of the curved extruded jug concept in this research is: Jugstrusion(s). The author presents this as description of the concept of creating ceramic jugs via the extrusion process, the full description is presented in figure 7:

Jugstrusion

juhg-stroo-zh*uh*n
noun
noun: **jugstrusion**; plural noun: **jugstrusions**

1 Jug shape created by the extrusion of plastic clay through an profile die "an extruded jug". Typically this kind of jug is handleless and with a curved profile to enable pouring.

Word constructed from:

- Jug (noun) noun
  - A large container usually made of earthenware, metal, or glass, commonly having a handle, a narrow neck, and sometimes a cap or cork.
- Extrusion (noun)
  - The act of extruding or the state of being extruded.

Fig 7: Description of the new term: Jugstrusion(s), proposed by the author.

Innovation Opportunities for Extrusion in Architectural Ceramic Production

The work with the extruded jugs resulted in a successful series of craft artefacts has been shown (and sold) at a number of high-profile venues and exhibitions. Regardless of the successful outcome of this research in a craft sector, the author saw opportunities for knowledge developed during the project as having potential to impact beyond the initial craft context.

As previously highlighted, the most extensive use of the clay extrusion process is currently in the production of architectural components such as bricks, tiles and pipes. The UK has an extremely rich heritage of ceramics being used for both structural and decorative purposes in architecture, particularly the Victorian period saw ceramics as a central medium for this application (Lloyd 1972). The extensive use and innovation in ceramics for architectural uses in this period, is likely to have been founded on the abounded availability of clay throughout the UK and a high number of local and regional manufacturers which had the capability to respond with a flexible production in relation to the requirements from architects and builders. During the 20th century the increased availability of concrete and glass challenged ceramics as one of the main materials for architectural construction, and UK lost significant ceramic production capabilities, with the decline of many smaller specialist firms (Hammond 1990). Throughout the 20th century ceramic manufacturing capacities became increasingly centralised within a few larger companies such as Ibstock, Hanson and Wienerberger, a structure that currently prevalent. Production methods in these companies includes both pressing and extrusion but both fabrication methods are overwhelmingly employed in mass productions scenarios with a focus on highly standardised products. While some of the companies still retain some capability for creating specialist ceramic components (generally for reproduction purposes) the industrial architectural ceramic sector's capacity to respond to new creative ideas remains limited. Darwen Terracotta is among the few manufactures in the UK that has the capacity to create bespoke components in response to requests from architects or designers. However, Darwen Terracotta's production is entirely based on slip-casting, which makes the manufacturing process very slow and the products very costly. Worldwide there are also relatively few companies that are capable of responding to request for bespoke ceramic parts for architectural applications. Boston Valley Terracotta (US) has in the last decade emerged as one of the leading companies in this market. The company offers a wide range of manufacturing capabilities including hand moulding, slip casting, ram pressing and extrusion – capabilities which enable the company to respond with great flexibility to a wide range of product requests. The company has actively sought the develop the market for bespoke ceramic production with initiative such as the Architectural Ceramic Workshop Assembly (ACWA), where teams from leading architecture firms are invited to work with the company on experimental projects . Ceramica Cumella (Spain) is also one of the few firms that has specialised in the capacity for responding to requests from architects for bespoke and specialist products. A few larger companies, including German NBK and the Italian firm Palagio, will also undertake specialist commissions as a part of their services. However, these companies are, in general, much more focused on high volume manufacturing.

Ceramic profile extrusion is an extremely efficient ceramic production method, but as previously highlighted for many decades innovation with the method has been very limited and the method is currently almost exclusively used to produce linear sections typically in mass production scenarios. The current phase of the research seeks to expand on the initial results and utilise digital fabrication technologies further to establish new approaches with the extrusion technique to extends conventional production capabilities for architectural ceramic components.

Development of Low-Cost Hydraulic Clay Extruder

One of initial challenges faced by the researcher in terms of developing the results from the craft-based extrusion experiments into knowledge that would be applicable in industrial production contexts, was the issue of access to industrial grade extrusion machinery. With the decline of the UK ceramic manufacturing sector, much of the supporting industry has been lost, including manufacturers of ceramics production equipment. The author was unable to source UK produced extruding machinery that would be suitable for experiments into architectural scale extrusion and had to resort to acquiring an extruding pugmill from a US based manufacturer. However, the particular model (VPN100TE) had never previously been sold in the UK and on arrival the machine was discovered to be inoperable due to incompatibility with UK electrical standards.

The author's difficulties in sourcing suitable extrusion machinery to carry out industrially relevant research highlights some the underlying challenges to innovation in this sector. The decline of specialist engineering firms, toolmakers and machine manufacturers is likely to mean that companies that seek to develop new products or services for this sector simply lack the supporting industry to do so.

This situation forced the author to look ways to address this situation and aspects of the Maker Movement seem to provide inspiration in this regard. The notion of self-building machines aided by online knowledge resources have been one of characteristic aspects of the DIY culture that has developed in Maker and Hacker communities (Hatch 2013). Inspired by this approach the author undertook the task of constructing his own extruder. An auger-based machine was deemed far too challenging to attempt, but a piston-based system seemed to have a reasonable prospect of realisation. As the core power unit, a hydraulic system was considered to be the most likely way to achieve the significant pressures required in the profile extrusion process, and standard, of-the-shelf, hydraulic cylinder and power unit were acquired. In this regard it is relevant to note that the author had no prior experience with hydraulic systems, and the basic knowledge for constructing a DIY system were largely draw from online knowledge resources, such as Colin Furze's YouTube videos (Furze 2019).

To create the extrusion cylinder, lengths of standard stainless-steel pipes were acquired via an online metal stockholder. Parts that were not readily available to buy as standard components, such as flanges and holding brackets for the cylinders, were fabricated by a local laser cutting firm and welded on.

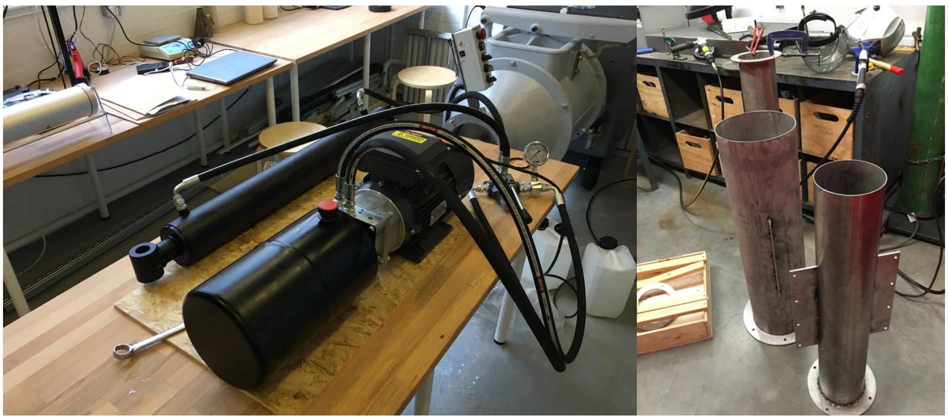

Fig 8: The hydraulic power unit on the left, with stainless steel tubes being fitted with flanges and brackets in the image to the right. Photos: T. Jorgensen, 2020.

The frame of the system was constructed with parts from the Unistrut system (mostly from a stock of university shelving surplus). Throughout the development and construction of the extrusion system an approach of direct construction without prior design plans or detailed drawings was employed. This methodology is closely associated with development methodologies employed in maker and hacker communities, which can be seen reflected in statements such as the 'Cult of Done' (Pettis 2016). Arguably, craft practice can be characterised by similar approaches, where trial-and-error based experimentation is typically the basis for the development of new ideas or projects. This type of methodology has the capacity to enable a rabid progression of a concept, particularly if reconfigurable systems are employed. In this particular case the use of the Unistrut system enabled iterative improvements to be easily implemented through the repositioning of parts.

Fig 9: The construction of the extruder frame, starting from top left with the 'raw' material consisting of surplus Unistrut components, clockwise to the near completed frame in bottom left image. Photos: T. Jorgensen, 2020.

The system that has now been established has the capacity to accommodate shapes with cross sections of up to 200mm, which enable architectural scale parts to be produced. The hydraulic cylinder can deliver pressures of up to 230 bars, which is significantly higher than the pressures that are typically used in the production of architectural ceramics, and even higher than the pressure that are utilised for specialist ceramic products, such as the filters for catalytic converters. While the system has very significant mechanical capabilities, the cost of the piston extruder is relatively modest at around £3000 (including all parts). Auger based extruders at this scale are significantly more costly, the £17000 paid for US build extruding pugmill (that was initially acquired for the project) provides an indication of the typical costs for this type of machinery. In this regard it is relevant to note that the piston extruder developed in this project does not have any mixing or vacuum capacities. The preparation, such as mixing and de-airing of the clay bodies, will have to be carried out prior to the extrusion stage, but this can be done through the use of any sized pugmills, clay mixer – or even through manual wedging or kneading.

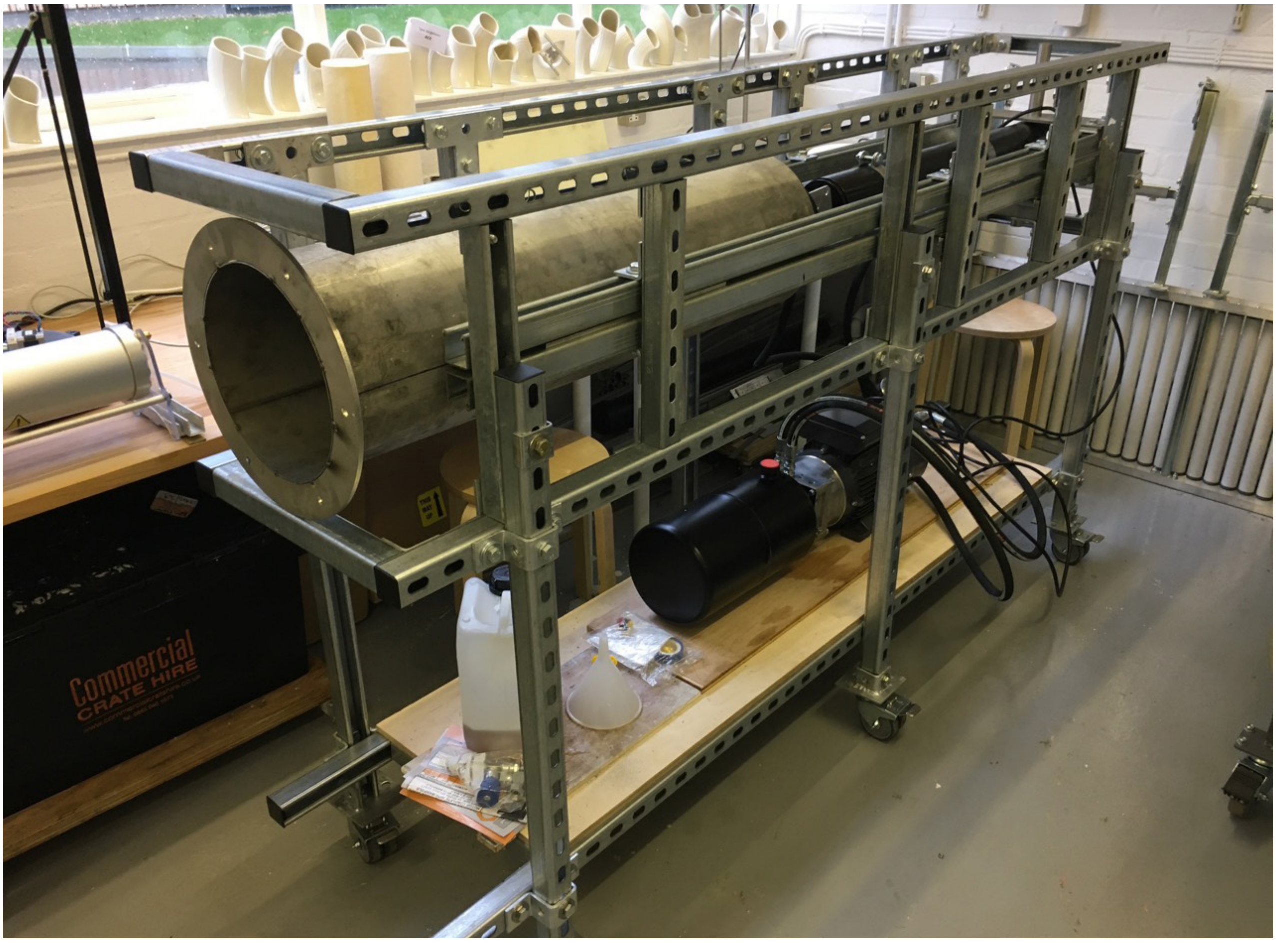

Fig 10: The completed hydraulic extrusion system. Photo: T. Jorgensen, 2020.

Further development of the parametric script for creating extrusion dies
In parallel with the development of the ram extruder system, improvements to the parametric Grasshopper script to create extrusion dies were also carried out to enable the software tool to perform in relation to architectural applications.

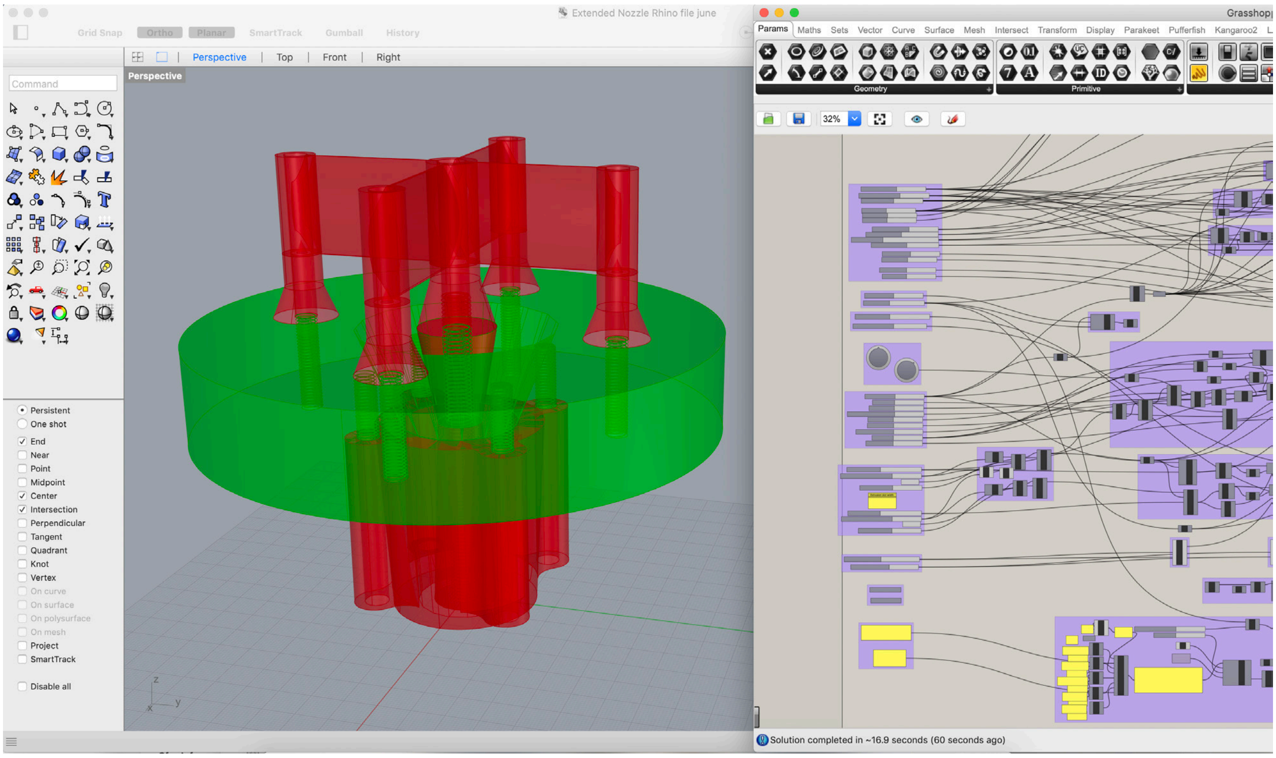

Fig 11: Development of the 3D die file via Grasshopper visual scripting. Visualisation of the die is to the left, with the pressure plate highlighted in green. The complex grasshopper script can be seen on the right with all user input via number sliders located to the left of the script. Image: T. Jorgensen, 2020.

One objective in this development was to develop the scrip to enable users with little CAD expertise to create 3D die design files. A key aspect in this regard was to enable automated generations of 3D geometries purely from numerical input. This objective was successfully achieved by developing the script with capacities of generating designs from number sliders that determines all the key aspects of the die design. The script also has the facility to automatically generate multiple, separate elements of the die, including a nozzle, a pressure-plate, bridge spacing legs and the bridge itself. The nozzle extends out to deliver the actual extruded clay shape. The nozzle is connected to the pressure-plate, which is the key section that absorbs the pressure from the clay being pushed by the hydraulic operated piston and directs it further via a tapered section into the nozzle. As previously mentioned, the bridge enables extrusion profile cores to be suspended, so shapes with hollow sections can be produced. In this principle the clay flow, which is initially separated by the bridge, is forced back to re-join through compression as it travels through the tapered pressure plate and further through the nozzle. This cutting of the clay flow by the bridge can in certain situations lead to weaker areas in the extruded clay parts, an issue which is described as 'seaming' (Händle 2007). In order to facilitate a better re-join of the clay the spacer legs 'lifts' the bridge from the pressure plate and thus provide the clay with more 'opportunity' to fully re-join before entering the pressure plate and nozzle. All of these various aspects are interrelated through the parametric scripts, but can also be adjusted individually through the use of the numeric sliders. The parts can, at any given stage, be exported out as Standard Triangulated Language (STL) files, which is the standard file format used to operate 3D printers. The various die parts can be 3D printed jointly as a complete kit, or in separate 3D printing operations. The only non-3D printed parts that is needed to construct a complete die is a set of stainless-steel bolts. In relation to these fixing bolts the Grasshopper scripts facilitate generation of female treads to be incorporated in the 3D printed die parts.

Initially this script was developed just to generate designs of tube shapes but work is now underway to enable the script to automatically generate dies from any 2D profile shape – with multiple hollow cores.

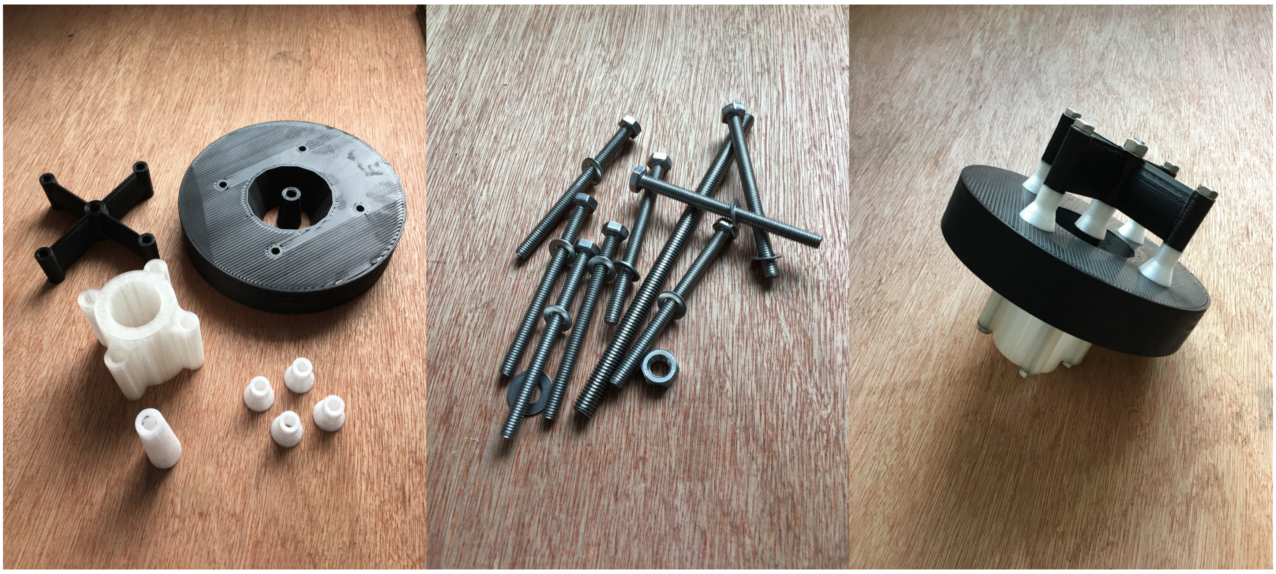

Fig 12: Components for a 3D printed dies, with the printed components to the left, stainless steel bolts centre and the complete assembled extrusion die on the right. Photos: T. Jorgensen, 2020.

Initial Test of Hydraulic Extrusion System with 3D Printed Dies

The initial test of the ram extruder and 3D printed dies from the improved Grasshopper script was carried out in February 2020. The ram extruder system was at this stage still lacking refinement and tuning, but still showed very significant potential. Extrusion pressures in excess of 50 bars was employed, which is more than the pressure levels that are commonly use in industrial brick making (usually around 30 bars). The Unistrut frame construction has so far shown no sign of stress deformations. Equally, the 3D printed dies tested with the system have also performed well with no breakages experienced. Two different diameter dies were tested with the system, both with a polygon textured outer surface in the extruded shapes to enable visual evidence of any distortion or twisting in the extruded test shapes. The production of straight extrusions was assisted by the use of upholstery foam in combination with a roller table to alleviate possible distortion of the soft extruded shapes. The system was also explored for the possibility of producing curved shapes through manual manipulation of the extruded forms during the extruding process. The implementation of such manipulations had some very promising early result and a number of radii were successfully implemented in the test pieces.

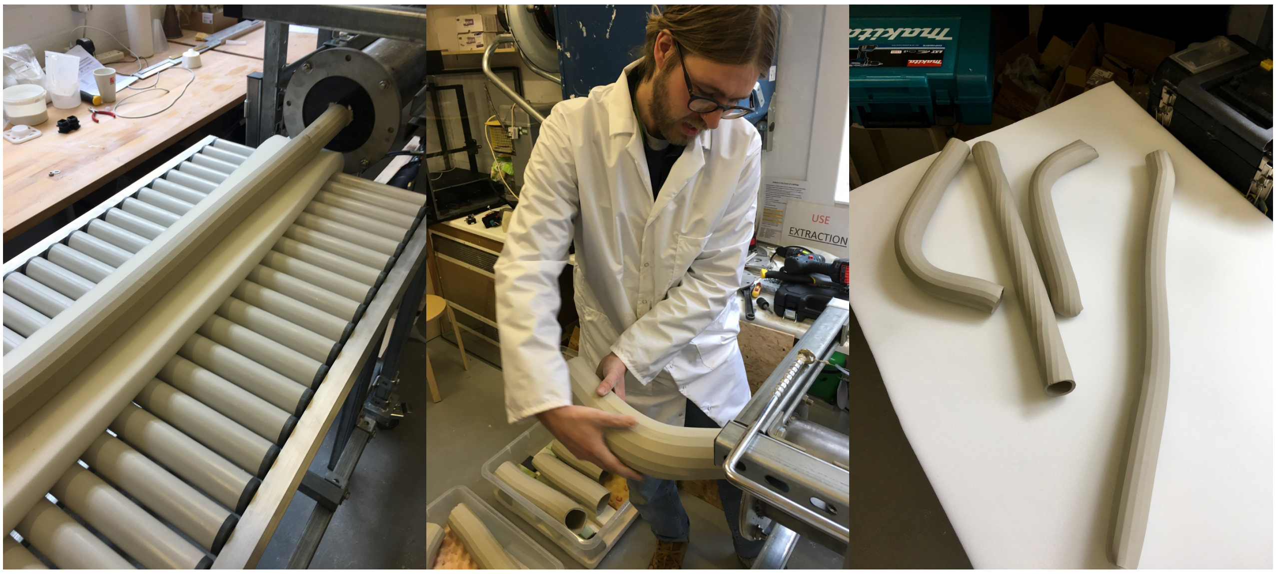

Fig 13: Initial test of the system, straight extrusion supported by upholstery foam on a roller table. Example of manual manipulation of extruded forms illustrated in the central image, and text extrusions on the image in the right. Photos: T. Jorgensen, 2020.

These manual tests served as preparatory studies to explore the clay's capacity for manipulation – tests that are informing the next stage of the research where such manipulation is sought implemented with collaborative robotic arms (commonly known as Cobots). The vision is to create an entire workflow which enable the production of curved extruded ceramic profiles as architectural components directly liked to digital design data so specific radii and curves can be produced with Building Information Modelling (BIM) data (see Fig 14).

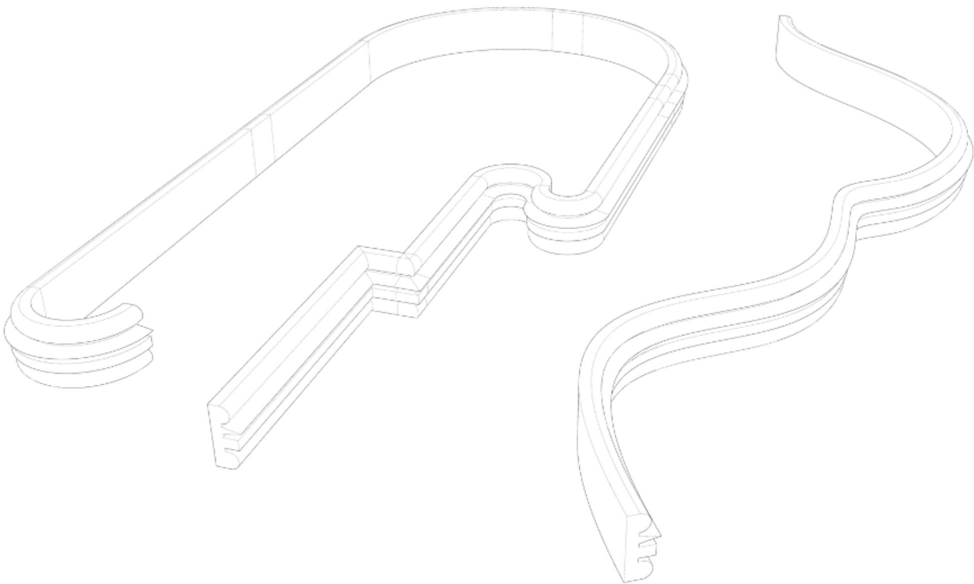

Fig 14: Illustration of the research's visions of being able to use robotic arms to bend a single profile into pre-defined radii and curves for architectural detailing.

It should be noted that some practical difficulties in the use of the system were also encountered in the initial feasibility tests, with a number of issues needing further development. An example of such an issue concerned the loading of clay. This process proved to be quite challenging, particularly without trapping air into the extrusion tube. However, experiment to alleviated this issue is now underway with concepts of using the hydraulic ram to assist in this operation. Options that are currently being explored includes pushing the clay into the back into the extrusion cylinder – or using the reverse power of the hydraulic ram to pull the clay into front of the extrusion system.

Discussion: Knowledge Transfer from Craft Research to Industrial Application

While the impact of the coronavirus has forced practical tests with system to be temporarily been suspended, a clear vision of creating impact with the research in industrial contexts remain. The motivation for this effort is driven by an ambition to provide an exemplar of how knowledge which has initially been developed in craft practice, can have real innovation potential in different sectors or scale of productions – in this case, the architectural ceramic industry. However, transferring knowledge between different sectors requires careful consideration so that knowledge contributions have a genuine value in the new context. This stage of the research is being developed with leading global companies as project partners including: Arup (engineering, architecture), Sibelco (clay and raw materials), Wienerberger (brick and architectural ceramics products) and Centre for Window and Cladding Technology (organisation for ensuring standards, construction guide lines and safety).

All these partners have different perspectives in terms of the project and recognising each particular partner's interest is critical to fully exploit the opportunities for knowledge transfer. Wienerberger is listed as the world largest manufacture of bricks, the company has headquarters in Austria, but has production sites throughout Europe, including 14 in the UK. For a large company like Wienerberger, which is primarily focussed on mass-production, production flexibility and new design development is highly likely to have a lower priority than product consistency and manufacturing efficiency. Issues in relation to these objectives includes the significant wear the extrusion machinery and dies are subject to in intensive production situations with the use of abrasive clay bodies. In these contexts, the concept of 3D printed dies is unlikely to present advantages over established approaches and conventional technologies. However, maintaining some capacity to respond to requests for bespoke or specialist components still seem to be valued by large scale manufacturers, perhaps as a way to support the sale of mass-produced products. Wienerberger still retains capacities for production of such specialist items in several of their plants, including Ewhurst and Sandtoft. For this kind of production, the capacity of being able to create extrusion dies for short production runs, quickly and cheaply via 3D printing is a relevant prospect and tests with this particular focus are scheduled to be undertaken in the spring of 2021.

The development of the hydraulic piston extruder system was undertaken to enable the research to progress despite the US build extruding pugmill being inoperable. However, the author considers the concept of this machine to be far more significant that just facilitating the progression of the research project. However, the development of the piston extruder is likely to be relevant in productions contexts different from the research into 3D printed dies. A piston-based extrusion system is hard to automate and therefore unlikely to be of interest to large established industrial production setups, such as those operated by Wienerberger. Even for the productions of bespoke and specialised products, large industrial manufacturers usually have spare auger extruders that are not operating on the main production line and therefore available to produce shorter run products. Such auger-based extruders will always be far more efficient in terms of production throughput, as clay can be fed continually through a hopper system to enable an uninterrupted productions flow. In contrast, a piston-based system will have to be stopped and refilled with clay each time the cylinder empties. While a piston-based extrusion system is unlikely to be relevant for the large industrial contexts described above, it could have significant potential in other architectural ceramic production contexts. For example, it is likely to be a more efficient production method than slip-casting, and consequently such a system could be relevant to companies like Darwen Terracotta, which currently rely entirely on casting for all their production. One of the other project partners, Arup, sees this as exciting potential. Arup has engaged in several high-profile building project with ceramic facades that has been fabricated by Darwen Terracotta, including One Eagle Place, Piccadilly and Edwardian Pastoria Hotels' new Leicester Square Hotel development. The slip-cast ceramic components produced by Darwen Terracotta is currently an extremely expensive option for facade cladding and the use of piston-based extrusion has the potential to lower the cost of certain shapes and extend options for using ceramics in bespoke building projects.

The low cost of the piston-based extrusion system also has the potential to lower the 'barriers to entry' for new venture into clay extrusion for architectural applications. The availability of such systems could encourage individual practitioners and small businesses to enter this field and contribute with new ideas, design and innovation. Inspiration for this vision of impact has been dawn from projects such as 'Precious Plastics' (2020), which has freely shared knowledge of self-build and low cost machinery for plastic manufacturing to encourage individual practitioners to develop their own production set-ups.

Reflections

This paper has described the initial craft-based experiments that led to the development of the larger research project. The initial experiments focused on the use of 3D printing to create a series of extrusion dies with particular geometries to affect the clay extrusions to curve as they emerged from the die. This process was undertaken with minimal manual intervention to enable variations in the jug forms (termed Jugstrustions by the author), and thus establishing a production concept to create series of unique pieces. Such an approach is considered to be consistent with a general craft practice context, where uniqueness of artefacts and variations in products are not only accepted, but generally celebrated. Using the concept of utilising digital technology to set up production situations that inherently results in a variable outcome the author proposes a new notion of: Technological Indeterminism. For the next stage of this research endeavour the author has sought to further development some of the core concepts with 3D printing of the extrusion dies, the use of parametric scripts and exploration of curved extruded shapes, but implemented in industrial contexts. Critically this phase of the research contrasts the initial experiments with a new aim of establishing processes that presents a high level of control over the extruded forms to ensure that the research is relevant to the requirements of the architectural industry. Shifting between research the context of craft practice to industrial production highlights the changing of emphasis for this research. This change of emphasis of using digital tools to develop approaches that celebrated the characteristics of the clay medium with the resulting variability in the outcome to a context where certainty and product consistency are some of the most central criteria for a production. It could be argued that David Pye's much quoted concept of 'workmanship of risk and workmanship or certainty' (1968) provides a relevant lens to view the two different phases of the research. Further in this regard, the author has found it interesting to consult with another of the project's industrial sector collaborators, Centre for Window and Cladding Technology (CWCT). This industry body works to ensure that architectural cladding components conforms to certain standards so to ensure safety, energy and environmental performance. Tests facilitated by CWCT on new building components can be costly, and this process in itself might be a limiting factor in industrial companies' appetite for innovation in this area. The rationale for developing a capacity for a manufacturer of architectural ceramic parts to undertake rapid product development through the use of 3D printed extrusion dies, could therefore be somewhat compromised by this aspect. Regardless of such challenges, the core aim of the second phase of this enquiry remains to transfer knowledge from craft-based research experiments into useful applications in industrial contexts. While concrete examples of such knowledge transfers are is still to be established, evidence that indicate that craft research is relevant beyond its own disciplinary boundaries could arguably be found in this project's capacity to attract the support from four very significant industrial partners, with in-kind support to the value of more that £30K being committed.

As a final remark it is also relevant to consider that the research in the industry facing part of the enquiry is likely also to provide opportunities for knowledge to flow in the opposite direction – so from the industry to the craft sector. The author is very mindful that solutions developed with industry applications in mind, may yet still find more relevant use in craft sector applications. 7The fundamental notion of recognising the value of knowledge exchange and interdisciplinary interaction as the fertile ground for innovation in all production contexts remains the core principle driving this research project.

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