EUROGRAPHICS Workshop on Graphics and Cultural Heritage (2019)
S. Rizvic and K. Rodriguez Echavarria (Editors)

Preserving ceramic industrial heritage through digital technologies

Karina Rodriguez Echavarria[1] Tim Weyrich[2] Neil Brownsword[3]

[1] Centre for Secure, Intelligent and Usable Systems, University of Brighton, UK
[2] University College London, UK
[3] Staffordshire University, UK

Figure 1: *Historic moulds used in the manufacture of ceramics at the former Spode Works, Stoke on Trent, UK. Copyright © Bjarte Bjørkum.*

Abstract

World-renowned for its perfection of Bone China and underglaze blue printing techniques, the historic Spode Works in Stoke-on-Trent was one of the few ceramic factories in Britain to have operated continuously on its original site until the company ceased trading in 2008. Since then the site has undergone many transitions with much of its former production infrastructure being discarded. Currently the site holds an estimated 70,000 moulds once used in ceramic production dating from the mid 19th century to 2008, which remain as critical elements of British industrial history at risk of disappearing. This paper presents on-going research which explores the application of 3D technologies to create digital surrogates to support the preservation of these Cultural Heritage artefacts, and ways through which their form and context can be explored to creatively disseminate the associated histories of their production. Given the complex nature of ceramic manufacturing as well as the large-scale of the problem, this is not an easy challenge. Hence, the research investigates workflows and technologies which can support creating a digital, and potentially physical, archive with a selection of mould typologies, shapes and complexities. To further understand the complexities of industrial craft practices, the resultant dataset also aims to elucidate material and craft knowledge embodied within such objects. For this, the research looks into novel manufacturing processes, such as 3D printing, to re-invent the physical shapes documented in these moulds in new interpretations of this historic legacy.

1. Introduction

Cultural heritage preservation is not only concerned with the ancient past; many towns and cities around the world contain heritage artefacts and spaces from recent history. These include the remains of industrial heritage - factories and manufacturing evidence from the industrial era, displaced in the late 20th century by the advances of automatisation and the surge of globalisation.

In this paper, we explore the role that digital technologies can play in safeguarding and preserving this heritage. In particular, we explore the challenges presented by the industrial processes whose legacy is sheer in terms of number of items. As such, we investi-

DOI: 10.2312/gch.20191355

gate the role of the digital surrogate or copy to preserve important information when it is not possible to preserve the physical material. Although we acknowledge digital information would never be a replacement to an original heritage artefact, we look at the practical choices which will have to be made in case there is no prospect of keeping and curating all physical artefacts.

The contribution of this paper is two-fold. On the one hand it provides an exploration of the role of digital technologies in the preservation of industrial heritage assets, in particular plaster moulds used within ceramic manufacture. The research addresses in particular the issue of scale and access. On the other hand, it proposes a fully digital pipeline for the documentation of this material from digitisation to reconstruction, and the physical reproduction of design data defined by the moulds.

In this research, we use the case of the industrial ceramic heritage in the city of Stoke-on-Trent. The context for this research is presented in Section 2. Section 3 describes related work in this area, followed by a digitisation trial (Section 4) investigating the digitisation of moulds for the preservation of this heritage. Section 5 then explores the reconstruction of the shapes determined by each mould; while Section 6 presents their physical reproduction. Finally, Section 7 presents conclusions.

2. Ceramic industrial heritage context

The six towns that constitute Stoke-on-Trent in the United Kingdom have been famed for their industrial-scale pottery manufactures since the early 18th century. By the 1720s, as tea drinking became firmly established in England, increased demand for finer ceramics led to the introduction of new wares and technological innovations, which changed the organisation of factories to accommodate these new techniques. Perhaps the most important development was that of a local workforce becoming increasingly skill-specialised through new divisions of labour, integrating a local population into an economy led by the manufacture of pottery.

Alongside pioneers of the industrial revolution such as Josiah Wedgwood and Josiah Spode, the Staffordshire potteries were driven by hundreds of relatively small factories with more than 2,000 kilns firing millions of products a year. In 1938 half the workforce of Stoke-on-Trent worked in the industry with employment peaking in 1948 to an estimated 79,000 people. However, during the last three decades, escalating global competition has resulted in many companies struggling to adapt or compete in both domestic and export markets.

Changes in lifestyle preferences, together with increased global competition, mainly from East Asia in the 1990's, forced many renowned factories to outsource manufacturing to developing economies where energy and direct labour costs were a fraction compared to those in the UK. This strategy, coupled with the advances of production technology, proved detrimental to a phenomenal concentration of human skills and knowledge in Stoke-on-Trent. Throughout this period much of the physical infrastructure - unique examples of industrial architecture together with many aspects of traditional know-how have been lost.

Figure 2: *Examples of Spode ceramics. Ruins of an Ancient Temple near Corinth. Copyright © Victoria and Albert Museum, London.*

2.1. Historic legacy of ceramic production: *Copeland Spode Works*

Before it ceased trading in 2008, the *Copeland Spode Works* in Stoke-on-Trent were one of the few ceramic manufacturing factories in Britain to have operated continuously for over 230 years on their original site. In this factory, the traditional Spode Bone China ceramics with underglaze blue printing techniques (see Figure 2) were manufactured.

The legacy of this factory was assigned to the Spode Museum Trust in 1987. This immense archive includes over 30,000 engraved copperplates, pattern books, tools and machinery, documents, photographic records and some moulds. Yet, prior to the factory's closure an oversight was made not to accession the majority of moulds due to their perceived value and the sheer space required to house such material.

An ongoing survey (which commenced in 2015) undertaken by Stoke-on-Trent city council, who now own the 10-acre site, and the vast majority of the moulds, has to date recorded in excess of 70,000 moulds that still remain within eleven buildings [Zoe17]. As the site is currently in the process of regeneration and its buildings re-purposed (see Figure 3), only a small percentage of this material has been recommended for retention. For the remainder, that survey stresses, "Those moulds not retained should ultimately be disposed of [...] a non-destructive disposal strategy would be the most preferred option for e.g. gift or transfer to a museum, other public organisation [...] destruction may ultimately be the only viable option".

As a result of the current pace at which the site is redeveloping and of the recommendations by the council, greater attention is being paid to this unique material to reverse its possible disappearance. The majority of moulds from the factory's recent history are considered by some stakeholders to have 'little historic value', but these should not be differentiated from early periods of manufacture from the Copeland Spode Works archive, as they still constitute an important piece of post-industrial history. As manufacture continues to involve a sequence of trial phases to test products, some prototype

Figure 3: *Site of the former Copeland Spode Works factory in Stoke-on-Trent.*

designs, if deemed inviable/too expensive to produce, would not proceed into production. So, potentially there exists a unique decorative design archive from various periods of history that have never seen the light of day since their inception/rejection. As 'by-products' of ceramic manufacture, moulds are rarely valued or preserved for posterity; the 'finished' ceramic artefact has always taken priority over those objects associated with labour. Yet as tools that revolutionised mass-production, they can illuminate the evolution of important technological changes in design and industry that remain relatively under-researched.

Scholarship within this area of material culture has tended to offer general historical overviews and insights into mould-making practices from early periods of industrialisation. The Prince's Regeneration Trust's investment in the Middleport Pottery (2010) led to the creation of a formal inventory documenting 12,000 moulds from the Burgess and Leigh factory in Stoke-on-Trent; yet access to this archive is limited to visiting the former Victorian factory, where practical issues, such as volume/weight and the very nature of the mould being an enclosed form, restrict analysis of the designs held within their negative spaces.

The Ceramic Century project initiated in 2000, produced film documentation of many of the craft skills including model, mould-making and the various casting systems associated with the various departments of the former Spode factory whilst it was operational. Although an important reference for research, it remains as raw footage and largely inaccessible within the Potteries Museum and Art Gallery's Archives.

In partnership with the Spode Museum Trust, Stoke-on-Trent City Council, Bucks New University, Staffordshire University, University of Brighton and University College London, this research aimed to investigate the role of digital technologies to document this historic legacy. These technologies include 3D digitisation technologies such as 3D scanning, photogrammetry, modelling and 3D printing. Hence, the research explored the role of the *digital surrogate* as a possible solution to document and preserve vital information for the future as well as to allows for wider access and (re)use of the digital content.

Although the use of 3D technologies for documentation of heritage is well understood, the particular challenges in this situation are associated with the huge number of moulds and their state which forces to make important choices as to how comprehensive the digital surrogate needs to be. An additional challenge is the IPR of the moulds and of the resulting digital surrogates.

In order to describe the methodology for the research, it is first necessary to describe the manufacturing process for ceramic production, as this will enhance a greater understanding of the different materials found at the site.

2.2. Process for the production of moulds

Ceramic manufacture involves various steps which separate the production of the shape, and surface treatment of the end product. Traditionally, shaping requires physically modelling the original form using a variety of materials. Mould-making can be a complex process, as it often requires casting the overall shape in multiple parts to facilitate removal and avoid undercuts [AMG*19]. Decorative ornamentation and other details such as handles and spouts are also modelled and moulded separately, therefore, increasing the volume of moulds needed to produce items such as tableware and ornamental wares. As a result this process yields a series of positive and negative objects which include:

- The **Model** (positive)
  This is the initial 3D form crafted from a series of design drawings. Due to the complexity of certain objects, models are formed separately in components to each yield a set of moulds. Evidence of the original models were difficult to locate as the model is often discarded following the creation of the 'master block-mould' yet, it should be possible to recover these shapes from the digital surrogates of associated moulds. To our knowledge, this has not been previously attempted.
- **Master Block** (negative)
  These are negative moulds cast from the model and can consist of numerous parts due to the models complexity (see Figure 4a). This is kept to provide a record of the item.
- **Master Case** (positive)
  These are positive moulds cast from the block to facilitate a 'master' shape, which is kept to provide a record of the item. An example is presented in Figure 4b.
- **Working block** (negative)
  These are negative moulds made from the master case.
- **Working case** (positive)
  Made from the working block whereby multiple working moulds can be made.
- **Working Moulds** (negative)
  A mould made from the working case. These moulds have a finite lifetime and can be easily reproduced from the case moulds.
- A **ceramic** cast is produced in parts from the working moulds using the slip casting process. These parts are later assembled.
- **Sprig moulds**
  These are press moulds used to create a shallow relief ornament (see Figure 8a). Sprig moulds historically were made from a low fired earthenware clay body and follow the same system of model, block case and working moulds yielding both positive and negative forms.

The expanse of moulds that still remain at the former Copeland Spode site include block-moulds, case moulds, and working moulds. The following section will describe related work in this area, followed by details of the feasibility study for their digitisation.

(a) *Examples of block moulds*

(b) *Example of case mould*

Figure 4: *Examples of moulds at the former Copeland Spode Works site.*

3. Related work

Given the physical strength of fired clay as a material, ceramic artefacts are popular finds in archaeological excavations. As such, the analysis, classification, reconstruction and study of ceramic artefacts has been an archaeological process which has attracted wide interest from the technical communities. So far, most research in this area has focused on creating computational methods to deal with the ceramic artefacts and not with the moulds used for their creation. Wilczek et al. [WMJ*18] present a survey of existing solutions to the time-consuming problem of orienting and drawing pottery fragments. Orientation is based on the 3D geometry of pottery models, which can now be acquired in minutes with low-cost 3D scanners. Other work in the recovery of shapes from fragments is available. These methods can recover both the ceramic shape and the decorations on the surface by automatic processes which unroll decorations into 2D planar space [LZW17]. Furthermore, there is also research on the automatic classification of pottery sherds which is a common problem faced by archaeologists [MD13, ZLS*19].

Moreover, there have also been efforts from the community towards addressing the requirements for the digitisation of large collections. Semi-automated solutions have been proposed for mass-digitisation which promise to ease the task of digitising existing collections [BTFN*08, SRF*17, Cyr19]. However, challenges still-remain with respect to the speed, portability, scalability and the accuracy of the digital outcome.

The following section will describe the feasibility study for the digitisation of a small sample of moulds on site in order to elucidate requirements for their mass digitisation.

4. Feasibility study

The aim of the feasibility study was to determine the most appropriate strategy for the documentation of the Spode moulds. This strategy includes the tools and workflow for digitisation to minimise cost and time. In order to determine this, we considered three aspects: 1) how to select the items to be scanned; 2) the technologies to be used; and 3) the process to document the moulds including issues such as access and documentation.

An initial set of moulds, sprigs and a sample of copper plates were digitised at the digitisation laboratory in Brighton, UK. The main objective was to understand how suitable was 3D digitisation for the three-dimensional moulds and whether technologies such as RTI could support the documentation of sprig moulds and copper plates. However, we acknowledge it will be impractical to bring items to the lab in the long term. Hence, we organised a trial where we will bring the equipment on-site.

The digitisation trial was conducted on site in Stoke-on-Trent, where we had access to a core sample of moulds selected for retention by Stoke-on-Trent City Council's Archaeology Service. This archive is recorded in an initial survey conducted in 2017, which offers a rationale for the shapes which were selected for retention, including factors such as age, uniqueness, and value in terms of technological developments and production process. This strategy provided a clear argument for prioritising this set for the trial.

The trial was performed over 3 days in July 2018. The team which performed the trial included two digitisation experts and a mould expert for overseeing and documenting the process.

During the trial, there was easy access to the moulds as this was conducted in one of the mould stores. However, this brought the obvious complexities with regard to infrastructure as there was no access to electricity and the mould stores were very dusty. Despite this, the team set up a mobile digitisation lab within one of the mould stores in order to undertake the digitisation. The equipment available included two 3D scanners: Aicon3D Smartscan, Artec Spider, tripods, a Canon 5D digital camera for photogrammetry and other infrastructure including electricity generator, laptops, turntables and lights.

In terms of documentation, the team continued working from the survey created by the city council which identified the moulds according to their location in storage. Other information we recorded included the digitisation operator, equipment and settings used, as well as the time/date when it was done.

Within the mould store, the moulds were piled up on shelves which contained a letter for their identification (see Figure 5). Thus, we introduced an identification system where for each mould we recorded the shelf identifier and a number to identify the levels of the shelf itself on which the mould was placed.

Although members of the council have already sifted and placed the moulds in the mould store, we found that a mould expert was still required to confirm what goes together. This is because moulds are not grouped according to the ceramic shapes for which their were produced, and pieces were missing in many cases. Hence, the mould expert's role included identifying pieces that belonged to the same shape by searching through the shelves and physically fitting moulds together. Another complication is that given the number of moulds produced during the mould-making process, it could be difficult to get a full set of parts of either the block or case mould. This is also why we decided to introduce a further identification element for the shapes to be digitised. This classification specifies whether the mould is a case or a block mould, as these were the moulds that were typically found in the mould store.

Figure 5: *Mould stores, Spode Works Stoke-on-Trent.*

The team followed a systematic process which is illustrated in Figure 6. The process involved a member of the team, with expertise in mould-making, visually inspecting the moulds on the shelves in order to select a variety of challenges, including: i) different complexity of shapes; ii) different sizes; and iii) different types of moulds.

Once the mould was selected, the individual pieces were separated for 3D digitisation. Thereafter, each piece was 3D scanned (Figure 7) or photographed for performing photogrammetry. We took certain decisions such as only scanning or photographing the area of the mould which contain information of the shape. Furthermore, all pieces were individually photographed and within their mould context for documentation purposes. The identification of each item was included in each photograph. This identification system and the visual documentation was important for the later post-processing of the data. This is because it is easy to find out how moulds fit together when they are physical, while it is much harder to do when browsing the digital models on screen. The photographs provide an intuitive documentation of how the various pieces scanned are assembled.

In total, we spent approximately 18 hours of digitisation over the

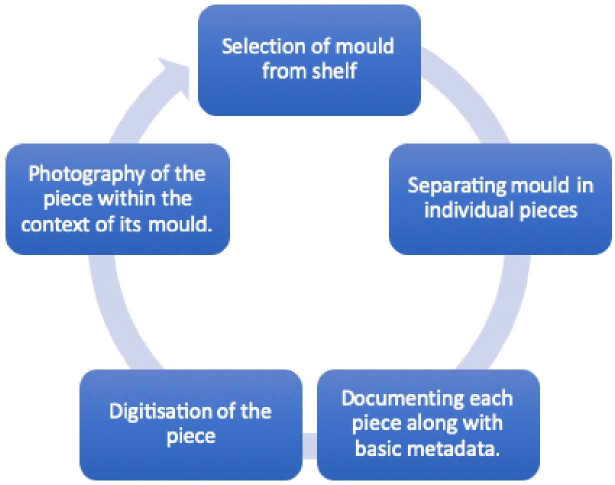


Figure 6: *Process for documenting moulds during the trial in Stoke-on-Trent.*

Figure 7: *3D scanning at the mould store.*

3 days. Other time was used for setting up the equipment, documentation and discussing strategies for scanning (e.g, automated rotation table vs hand-held scanner). There were over 25 mould pieces recorded with the 3D scanner which belong to eight moulds.

The following section will describe the digital outcomes and how they were post-processed.

5. Digital outcomes and their evaluation

The digital outcomes of the trials included a combination of RTI files, 3D scanned files and photos which were later used to process 3D models via photogrammetry. The latter were mainly used for comparison purposes with the 3D scanned files.

Figure 8b illustrates the digitisation outcome from the initial experiments done at the lab. The RTI technology worked well for both sprig moulds and for the documentation of copper plates. It demonstrated to be a suitable technology which can be much faster deployed than 3D scanning for the sprig moulds and still document important information on the relief.

(a) *Example of sprig mould in the Spode archive*

(b) *Normal map acquired from RTI acquisition of a sprig mould*

Figure 8: *Digitisation of sprig mould using RTI technology.*

Furthermore, Figure 10 illustrates the 3D models acquired via 3D scanning during the on-site trial. The 3D models were generated using the AICON OptoCat software available with the 3D scanner. These 3D models document 25 mould pieces which belong to 8 different ceramic shapes. Although they do not represent the full set of moulds for each shape.

Furthermore, we compared the quality of the 3D models generated both via 3D scanning and photogrammetry. The objective of this task was to compare the accuracy of the photogrammetry method and the quality of the data generated by both methods. Figure 9 presents the comparison between both 3D meshes. This uses the Hausdorff distance computed with MeshLab to determine the similarity between both 3D meshes. The deviation between the two models has a maximum of 6.155249 and a mean of 0.171816. The root means square deviation is 0.402617. These values are somewhat high, as the photogrammetry model contains less information than the 3D-scanned model. Nevertheless, the visual comparison demonstrates the data of both methods is very similar with the photogrammetry model containing significantly more noise when compared to the 3D-scanned model.

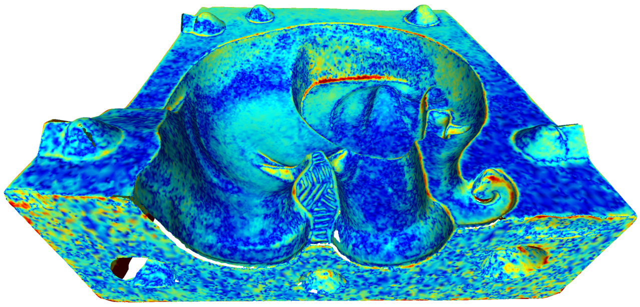


Figure 9: *Hausdorff distance between photogrammetry and 3D-scanned model.*

Therefore, the 3D models generated both via 3D scanning and photogrammetry were deemed to be suitable digital surrogates for the moulds.

Reflecting on the digitisation process, we found that photogrammetry was faster on site than 3D scanning, but it required more time off-site for post-processing. Furthermore, as the moulds are easy to 3D-scan, a rotation table with a scanner on a tripod was the faster way to get them scanned. We also made other decisions, such as not recording the base, as this tended to be flat or follow a round curvature. This information was deemed to be easy to synthesise at a later stage. The 3D scanning done on site will be completed in between 10–30 minutes per mould, depending on its complexity. Moreover, very little post-processing was required to close holes and generate a 3D mesh. Hence, a 3D-scanned mesh could be completed within 40–60 minutes in total. On the other hand, photogrammetry required of the operator transferring the images to a computer and post-processing the data. Although this work can be automated to a certain extent, overall there was more time spent with the latter method.

5.1. Reconstruction of ceramic designs

The digital surrogates provide tangible evidence of the surfaces for a variety of ceramic designs defined either by the positive or negative spaces of the moulds. The reconstructions of these ceramic designs was also of interest as they have a potential to be re-used in creative processes. In order to reconstruct a design, it is necessary to gather enough moulds which contain information on the shape. In addition, it is necessary to identify the type of mould (e.g. a block or a case) which the digital surrogate represents. Currently, this process is manual and it requires of a user to inspect visually the data.

An example of a collections of moulds is illustrated in Table 1. These moulds contain the design of a *falcon* composed by various parts: body, feet, head and beak. These parts do not overlap and it is not easy to determine how they fit together. In this case, we successfully identified various pieces coming from case or block moulds. As the table shows, in many cases we were not sure how many pieces in total the moulds should have.

These challenges which are common to all other moulds in the mould store make it difficult to identify a workflow which can potentially recover the original shape of the moulds for their preservation without the need for an operator to do this manually.

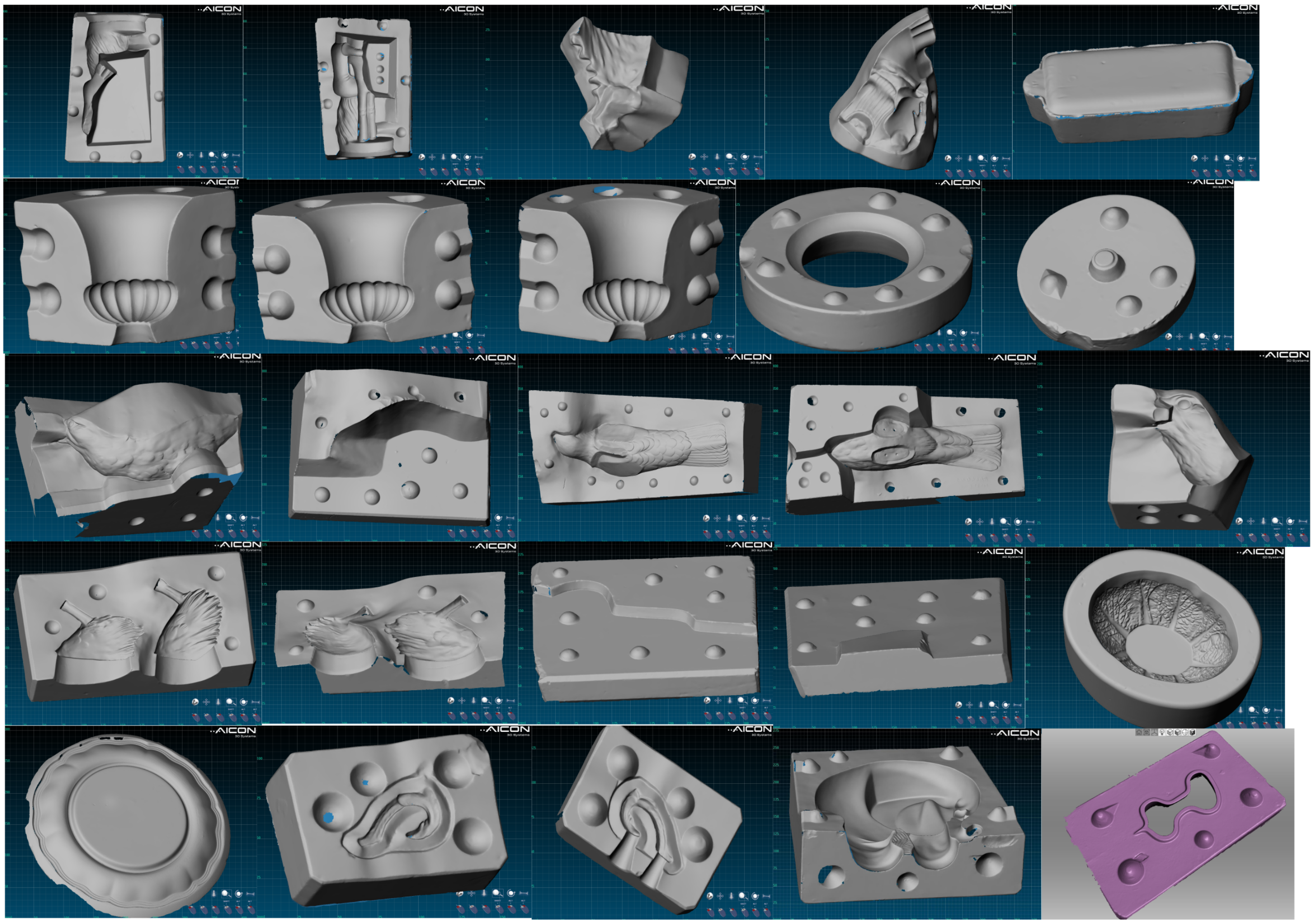


Figure 10: *3D models of scanned moulds.*

Num	Name	Parts digitised
1	Side body case mould	4/4 parts
2	Bottom body case mould	1/? parts
3	Top body case mould	1/? parts
4	Legs block mould	2/2 parts
5	Feet	No parts found
6	Head	1/4 block moulds
7	Beak	No parts found

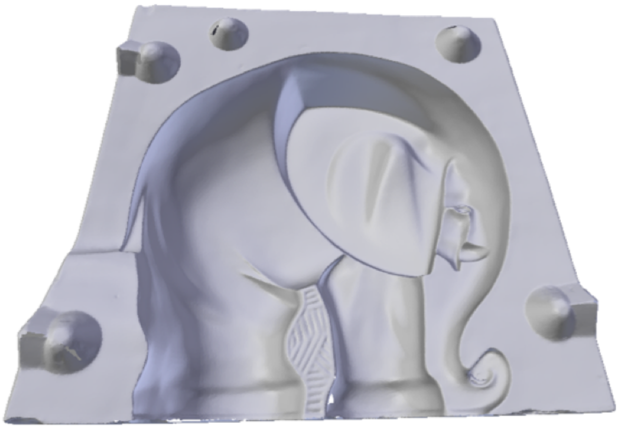
Table 1: *List of parts for the* falcon *ceramic shape.*

Despite the challenges, we experimented with reconstructing one of the more simple object shapes: the *African elephant* shown in Figure 11a, attributed to Eric Olsen from 1935.

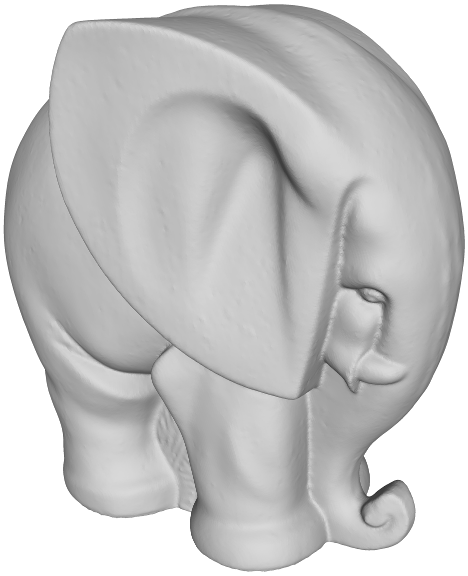
We made use of several tools for processing 3D meshes and modelling to generate the reconstruction of the ceramic shape. In particular, the implementation of the workflow uses a mixture of tools, such as Meshlab, Meshmixer and OpenSCAD. OpenSCAD is a free Computer Aided Design (CAD) software which uses the Computational Geometry Algorithms Library (CGAL) [The14] as its constructive solid (CSG) engine. Its script syntax uses a functional programming approach to generate geometry. By using these tools, we followed the process described below:

1. Removing faces from the 3D mesh to leave only the shape of the artefact for which the mould has been produced.
2. Invert the normals of all faces in the 3D mesh.
3. Duplicate the 3D mesh and mirror the geometry to obtain the other side of the artefact.
4. Bring the two sides of the 3D mesh together so that there is some intersection and perform a Boolean intersection operation.
5. Digitally sculpt the joining line so that this is no longer evident in the resulting 3D model.

The resulting 3D mesh is illustrated in Figure 11a-bottom. This process for reconstructing the Figure 11b. This process for reconstructing the shapes in the moulds can be extended to deal with other moulds as long as there is enough information for the reconstruction. The use of symmetry to complete certain shapes where there is information missing was also deemed to be an advantage of having a digital surrogate to work with. Finally, the ability to re-scale and make further modification to the reconstructed shape was very useful when we look at physically recreating the shapes in the mould.



(a) *3D model of mould for the* African elephant *shape*



(b) *Reconstruction of the shape by using symmetry*

Figure 11: *3D model of mould and corresponding reconstruction of the ceramic design.*

6. 3D printing

While the 3D digital surrogate was one of the main outcomes of this research, we had an interest to investigate the creative and industrial potential of such historic archives. This is because we envisaged that the data could provide further value for either creating re-interpretations of the archives or for creating further digital outcomes which might be of interest to the ceramic industry.

In order to investigate the creative and industrial potential of the digital surrogates, we looked at technologies such as 3D printing as these are not only becoming popular in Cultural Heritage, but they are also permeating industrial sectors, including ceramics.

3D printing is revolutionising the way industries can manufacture low-volume series of products. This is because 3D printing enables the digitisation of the product development process from idea generation to commercialisation. As such companies are no longer constrained by economies of scale and the capital assets required for analogue production as 3D printing is devoid of the need for mould-making and tooling.

However, the wider adoption of 3D printing for ceramics is still withheld by some shortcomings of the technology, including high costs, the limited materials available, as well as their inferior and anisotropic mechanical properties [NKI*18]. These processes normally print a raw or 'green part', which is a mixture of materials, including ceramic particles with or without binders. Some technologies require subsequently a a debinding processes in order to remove the binder from the part. Thereafter, a sintering process is performed in a kiln which consolidates the part and densify the ceramic.

There are high-end 3D printers available for ceramics [3D 18]. Further research and development to create new composite materials has resulted in new experimental materials, such as the ceramic resin produced by Formlabs [For18]. In this research, we used this stereolithography process using the Formlab2 printer to experiment with 3D printing the ceramic shapes. This process is based on binding molecules of resin by light.

The process for 3D printing involved first making some modifications to the digital shape. These are required to take into consideration the practicalities of 3D printing, for instance to allow resin to flow out of the 3D printed shape rather than remaining trapped inside. For this, the 3D mesh was re-scaled to be 100 mm tall in order to fit within the printing volume. The 3D mesh was then solidified, which is the process of adding depth to the surface. The thickness usually depends on the design intentions and the material specifications. We have experimented with thicknesses ranging from 2 to 7 mm. We also add two holes at the bottom of the shape, with diameters of 1.5 or 2 cm to let material escape.

The 3D printing process took normally around 12 hours. During this process, the 3D printer needs to support the weight of the printed shape (see Figure 12). The density of the ceramic material (1.9 g/cm^3 when fired) is much higher compared to other 3D printing materials, such as ABS (0.9 g/cm^3) and PLA (1.25 g/cm^3). Hence, the shapes require of a large amount of support material. For example, two thirds of the material used for the 3D printed shape was wasted in support. Once the print was completed, the part needs to be post-processed by washing it in IPA (isopropyl alcohol) for cleaning.

Thereafter, the supports are removed from the print and the 3D printed shape is sanded in order to smooth down the marks left by the support (see Figure 13).

Finally, the 'green' compact part is placed in a kiln for sintering as illustrated in Figure 14. The complexity of this step cannot be underestimated, as the selection of temperatures and timings for heating and cooling the part gradually can determine the success of failure of the final part. During this stage we collaborated with the technicians at the ceramics department who have more expertise with timings for firing ceramic shapes.

We performed 3 experiments for firing the shapes in the kiln using the timings shown in Table 2. These timings were selected following the material supplier's recommendations and their advice.

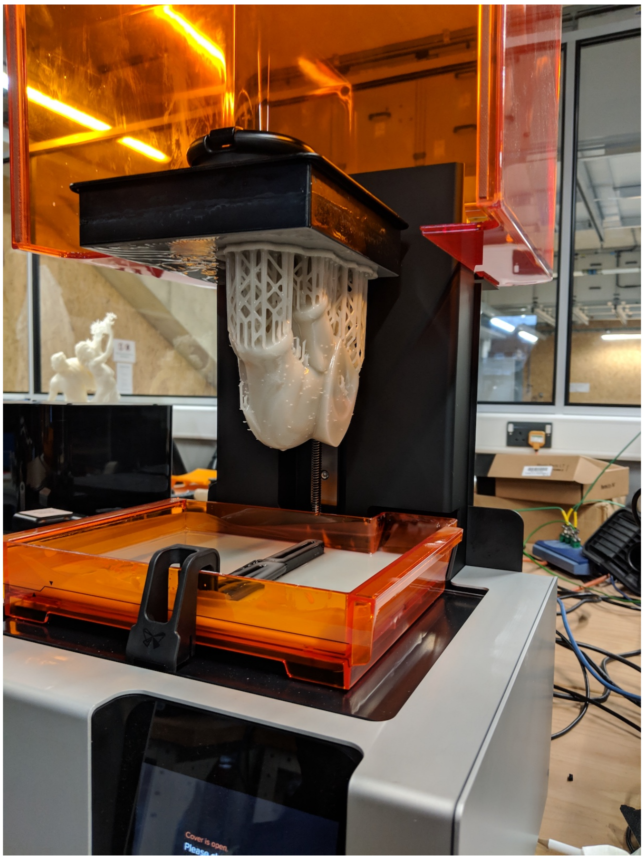


Figure 12: *3D printed* African elephant *shape in Formlabs2 3D printer.*

Unfortunately, none of these timings succeeded in producing a good part. Further experimentation took place in collaboration with the material supplier and it was agreed that further research is required to support the part during firing to allow the air to escape from the part while offering support so that the part does not collapse. Hence, this is a research challenge which requires further work.

Experiment	Timings
1st Firing	60°/hr – 240° hold for 8 hours
	60°/hr – 300° hold for an hour
	160°/hr – 1270° hold 5 mins
2nd Firing	60°/hr – 240° hold for 8 hours
	60°/hr – 300° hold for an hour
	160°/hr – 1240° hold 5 mins
3rd Firing	60°/hr – 600° no hold
	180°/hr – 1240° no soak (hold)

Table 2: *Timings for different firing experiments performed for the 3D printed shapes.*

7. Conclusions and further work

This paper has presented research on documenting the legacy of industrial heritage, in particular the tangible evidence of manufacturing processes. We focused on moulds used for the manufacturing of ceramic bone china from the former *Copeland Spode Works* site in Stoke-on-Trent, UK. As demonstrated by the research, these moulds constitute a ceramic design archive. They are also physical evidence of the processes developed by highly skilled people who worked in these factories.

Figure 13: *3D print of* African elephant *shape after post-processing in IPA (isopropyl alcohol), removed supports and sanded.*

Figure 14: *3D printed elephant shape in the kiln ready for firing.*

Given the current threat to many of the industrial heritage around the world, this research explored the roles of 3D technologies for the documentation of physical objects within the factories. The research outcomes include a better understanding of the processes which will be required to produce a digital archive of the moulds under threat, as well as a sample of the shapes of the archive. The research also showed the many challenges in dealing with this heritage material and the potential of these technologies to re-create the physical archive in materials such as ceramics.

Further work includes taking forward the lessons learned from this research in order to prioritise further digitisation efforts as well as to explore further the re-use of digital surrogates. There are further research challenges which can support this direction by developing automation both for digitisation and the reconstruction of the shapes. Finally, the 3D printing of ceramics also presents various challenges in order to successfully reproduced the ceramic shapes.

8. Acknowledgments

We would like to thank the Stoke-on-Trent City Council and the Spode Museum Trust for their support in this research. We will also like to extend our thanks to Alma Boyes, expert in ceramics, for supporting the sintering process as well as the technicians who supported the trials, including Daniel Brooks, Tanya Gomez and Eusebio Sanchez Pomares.

References

[3D 18] 3D CERAM: 3d ceram printing solutions, July 2018. URL: https://3dceram.com/en/. 8

[AMG*19] ALDERIGHI T., MALOMO L., GIORGI D., BICKEL B., CIGNONI P., PIETRONI N.: Volume-aware design of composite molds. *ACM Trans. Graph. (Proc. SIGGRAPH) 38*, 4 (July 2019), 110:1–110:12. URL: http://doi.acm.org/10.1145/3306346.3322981, doi:10.1145/3306346.3322981. 3

[BTFN*08] BROWN B. J., TOLER-FRANKLIN C., NEHAB D., BURNS M., DOBKIN D., VLACHOPOULOS A., DOUMAS C., RUSINKIEWICZ S., WEYRICH T.: A system for high-volume acquisition and matching of fresco fragments: Reassembling theran wall paintings. *ACM Trans. Graph. 27*, 3 (Aug. 2008), 84:1–84:9. URL: http://doi.acm.org/10.1145/1360612.1360683, doi:10.1145/1360612.1360683. 4

[Cyr19] CYREAL: Apachs: Accessible photogrammetry for the arts, culture and heritage sectors, 2019. URL: https://www.theaudienceagency.org/insight/case-in-point-accessible-photogrammetry. 4

[For18] FORMLABS: Introducing ceramic resin for the form 2, May 2018. URL: https://formlabs.com/blog/introducing-ceramic-3d-printing-form-2/. 8

[LZW17] LIU Y., ZHANG B., WAN L.: Automatically unrolling decorations painted on 3d pottery. In *Proceedings of the Computer Graphics International Conference* (New York, NY, USA, 2017), CGI '17, ACM, pp. 37:1–37:6. URL: http://doi.acm.org/10.1145/3095140.3095177, doi:10.1145/3095140.3095177. 4

[MD13] MAKRIDIS M., DARAS P.: Automatic classification of archaeological pottery sherds. *J. Comput. Cult. Herit. 5*, 4 (Jan. 2013), 15:1–15:21. URL: http://doi.acm.org/10.1145/2399180.2399183, doi:10.1145/2399180.2399183. 4

[NKI*18] NGO T. D., KASHANI A., IMBALZANO G., NGUYEN K. T., HUI D.: Additive manufacturing (3d printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering 143* (2018), 172 – 196. URL: http://www.sciencedirect.com/science/article/pii/S1359836817342944, doi:https://doi.org/10.1016/j.compositesb.2018.02.012. 8

[SRF*17] SANTOS P., RITZ M., FUHRMANN C., MONROY R., SCHMEDT H., TAUSCH R., DOMAJNKO M., KNUTH M., FELLNER D.: Acceleration of 3d mass digitization processes: Recent advances and challenges. 99–128. URL: https://doi.org/10.1007/978-3-319-49607-8_4, doi:10.1007/978-3-319-49607-8_4. 4

[The14] THE CGAL PROJECT: *CGAL User and Reference Manual*, 4.4 ed. CGAL Editorial Board, 2014. URL: http://doc.cgal.org/4.4/Manual/packages.html. 7

[WMJ*18] WILCZEK J., MONNA F., JÉBRANE A., CHAZAL C. L., NAVARRO N., COUETTE S., SMITH C. C.: Computer-assisted orientation and drawing of archaeological pottery. *J. Comput. Cult. Herit. 11*, 4 (2018). URL: http://doi.acm.org/10.1145/3230672, doi:10.1145/3230672. 4

[ZLS*19] ZHOU J., LU Y., SMITH K., WILDER C., WANG S., SAGONA P., TORKIAN B.: A framework for design identification on heritage objects. In *Proceedings of the Practice and Experience in Advanced Research Computing on Rise of the Machines (Learning)* (New York, NY, USA, 2019), PEARC '19, ACM, pp. 62:1–62:8. URL: http://doi.acm.org/10.1145/3332186.3332190, doi:10.1145/3332186.3332190. 4

[Zoe17] ZOE SUTHERLAND, STOKE-ON-TRENT ARCHAEOLOGY SERVICE: *Quantification and assessment of moulds at the former Spode Pottery factory Church Street Stoke-on-Trent*. Produced for Stoke-on-Trent City Council, February 2017. 2