INCORPORATING DIGITAL TOOLS WITH CERAMIC CRAFTING:DESIGN AND FABRICATION OF LIGHT DEFUSING SCREEN SHELLS

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ABSTRACT

This paper investigates the possibilities arising in design and fabrication of ceramic building components, by incorporating digital tools. In particular, we are presenting how traditional ceramic crafting fabrication methods could be enriched with parametric, performative and generative design techniques, alongside digital fabrication technologies.

Considering the growing importance of ceramic components in architectural construction, due to their economic and environmentally friendly properties, this paper highlights the findings of design led research experimentations, demonstrating potential innovative solutions and failures arising through a digitalised file to factory design approach.

Keywords: *Digital design, digital fabrication, parametric design, performative design, ceramic fabrication*

1. INTRODUCTION

Ceramic materials can be traced in various structures across the world since the beginning of architecture. Ceramic components such as bricks and tiles are being used as structural, cladding or decorating elements up to our days, in almost every building type and any geographic location. Among clay's most unique features is its flexibility. Being in a humid condition and by using some of the traditional crafting techniques such as, slab forming, extrusion or slip casting, clay can be formed in almost any shape.

For at least 15 years, computational design and fabrication tools have been increasingly applied in designing and constructing architecture as well as various types of building components. Parametrisation of design solutions (e.g. through rhinoceros and grasshopper) enables new possibilities in almost every construction and fabrication sector. Digital technologies such as 3D printing, CNC milling and CNC cutting are becoming applicable in all types of building materials or composites [1], including ceramics.

However, despite the wide use of ceramics in construction, most components remain planar, geometrically simple, and are commonly applied in standardised, rectangular formats. They barely explore innovative forms; complex geometries double curved solutions or performative optimisation embedded in their design process are rarely found. The largest part of ceramic building component production is still based on Cartesian geometries and two dimensional forming principles, focusing mostly on innovations in colours and glassing, rather than performative or geometrical aspects.

Looking at the current professional architectural press, ceramic innovation is rarely found. Realised, experimental projects, such as 'Vila Nurbs', by Geli [2], 'the Spanish Pavilion' by Foreign Office Architects [3], or the 'Urban Guerrilla' installation by GGlab [4], where double curved ceramic tiles were designed and fabricated out of clay slabs formed on CNC milled formers, remain an exception.

There is however a small number of innovative research groups, focussing on incorporating digital tools in ceramic design and fabrication, mostly 3D printing technology and robotic fabrication applications. The 3D printed bricks by Building Bytes [5], the 'PolyBrick' by Sabin, Miller, Cassab and Lucia [6], or the Contour Crafting robots used by Roche [7] are among the most promising precedents to be mentioned. Gramatio and Koehler's robotic brick walls assembly research [8], initiates an entire glossary of formal freedom in brickworks.

Celanto and Horrow are also investigating ceramics and 3D printing, however focusing on micro structure of ceramic skin [9]. Martin Bechtold's work with ceramic systems and digital fabrication [10] is among the most thorough, advanced research in the field. In his ceramic shading system prototype, he is the first to integrate environmental design strategies (e.g. radiance) and robotic fabrication workflow, a project, which was very influential for our research [11]. So is his research about industrialised ceramic robotic fabrication flow [12].

The fusion between traditional ceramic crafting techniques and digital design and fabrication though, remains still largely unexplored. It appears that a potential synergy between emerging computational technologies and ceramic crafting [13], such as slip casting, slab forming and extrusion forming has not been sufficiently explored as in other industries. In timber construction for instance, the synergy between crafting and digital technology, enabled innovative solutions of craft-like timber joints as demonstrated by Weinand and Hudert in the 'Timberfabric' project [14], reviving haptic qualities in architecture long lost through industrial automation.

Such qualities can be found by looking at presidents made out of other casting materials, such as the concrete shading screens presented in Erwin Hauer's Continua [15], the great potential ceramic components can achieve in terms of innovative geometry arises. Due to their high sculptural qualities, Hauer's pre-computational, concrete shading screen modules were highly inspiring for this research project. However, since they have been produced in a top-down approach, they do remain standardised form driven solutions, without incorporating any performative qualities, such as structural efficiency or lighting optimisation. Describing his "*Design 3*" screen project he admits:

"*The structure as it relates to physical gravity and construction was a secondary consideration in the design process and it turned out to be a considerable tour-de-force. They did not say it could not be done, only that there were no procedures in the books to calculate its physical requirements."* [15].

By incorporating digital design and fabrication techniques with traditional ceramic crafting methods, formal complexity made possible by the use of clay could be combined with performance. As a continuation of the 'Responsive Façade' research project [16] by Dutt and Das, where 3D printing was combined with slip casting techniques in order to develop façade components, we decided to extend this research to other ceramic production methods and asses their potential in a bottom up design process.

In particular, we have investigated the combination of laser cutting, CNC milling and 3D printing technologies with slab forming, extruding and slip casting techniques, performance based, file-to factory production process. All digital fabrications were used for producing formers, moulds and prototypes, which were then incorporated with one of the ceramic crafting techniques. Success or failure of this triple merge shall be assessed on the feasibility of the entire design to production process as well as on the quality and innovation of the final product. Could such a production flow offer innovative solutions in ceramic production and encourage the development of new products not existing today?

2. RESEARCH QUESTIONS AND METHODS

2.1. Research Questions

As a reaction to all previously described observations, the following research questions arose:

- How can we embed parametric design tools in the design process of ceramic building components?

- How can we incorporate CNC milling, CNC cutting and 3D printing technologies into ceramic crafting fabrication techniques, such as slip casting, extruding and slab forming?

- How can digital optimisation techniques pre-inform the design of ceramic building components in a bottom up design process?

- How can conventional ceramic design and fabrication process benefit by the incorporation of digital technologies? Can the use of new technologies encourage the development of innovative ceramic solutions?

2.2. Research method

To answer the research questions mentioned above, a collaborative, research led design workshop was launched, involving postgraduate and undergraduate students from Liverpool's School of Architecture. It was a selective process, aiming to assess and evaluate three different file to factory methods, where digital tools were combined with ceramic fabrication techniques. The process (figure 01) should enable a feedback loop, thus potential findings during the process could inform the initial starting point. In a second stage beyond the workshop's completion, the most promising design experiments in relation to each 'file to factory' method explored were developed further, leading to the production of 1:1 prototypes.

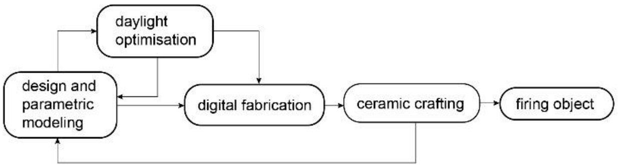


***Figure 01**: file to factory fabrication diagram*

During the workshop, participants were asked to collaborate in groups, thus each cluster of groups could examine three different aspects of the proposed 'file to factory' methods listed below, with an increasing complexity factor. Each work flow could be easily repeated in case of failure or necessity.

1. Digital modelling using Rhinoceros > optimisation using Ecotect > digital fabrication using CNC milling and laser cutting > ceramic fabrication using slab forming > firing the outcome.

2. Digital modelling with Rhinoceros and Grasshopper > optimisation with the Grasshopper plug-in Geco and Ecotect > digital fabrication using CNC milling and laser > ceramic fabrication using extrusion and extrusion forming > firing the outcome.

3. Digital modelling with Rhinoceros and Grasshopper > optimisation with the Grasshopper plug-in Geco and Ecotect > digital fabrication using 3D printing > ceramic fabrication using slip casting > firing the outcome.

All three methods were assessed by designing, optimising and fabricating light diffusing, ceramic screen components, to be applied as a suspended ceiling for a hypothetical gallery space, covered by a glassed roof, without any windows on the surrounding walls. Light diffusing devices are commonly used in museum or galley spaces in order to ensure constant, diffused daylight flow within the space. Available products today are mostly louver like components out of metal or plastic materials. There are no ceramic light diffusing screen products currently on the market. Each of the three file production methods was aiming to develop a non-existing ceramic product, which should fulfil innovation criteria in terms of nonstandard form, performance and materiality (ceramic).

Each scheme had to follow a set of constraints determined by the size of the available kilns, the budget, as well as the material properties of the various clay types. Thus, we decided to fabricate all prototypes in 1:2 scale. After processing the three different design and fabrication methods, our finalised results were collected, analysed and evaluated in terms of feasibility, possible conflicts of production methods and adaptability to the material properties, in order to achieve a set of conclusions, which could re-inform the entire process.

Our available facilities for applying both fabrication methods were the School's digital fabrication laboratories, as well as the ceramic fabrication workshops of Liverpool - Hope University. Our available hardware equipment included a Zprint 3D printer, a 3 axes CNC router, a laser cutter, ceramic slab forming facilities, clay extruders and several kilns.

In the following chapter, we will present three design explorations, one for each file to factory approach assessed.

3. CERAMIC FABRICATION DESIGN EXPLORATIONS AND RESULTS

3.1. Double curved louvers

The first design exploration investigates 3D modelling design and simulation techniques in combination with laser cutting, CNC milling and slab forming fabrication methods (figure 02).

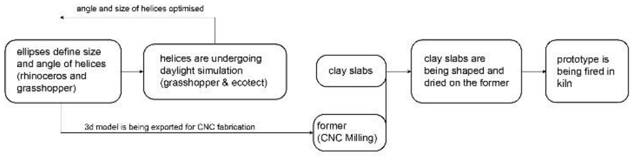


Figure 02*: file to factory fabrication diagram using slabs and CNC milling*

The screen component was conceived as a double curved ceramic louver system (double curved slabs), which would disrupt direct transmission of light from ceiling to floor using its curved surface to dilute the rays of light, thus producing light diffusion. Each component was designed to be suspended from the ceiling in an array with an overlap (figure 03), forming a homogeneous surface. Suspension from the ceiling would take place by adding a metal fixing through the hollow, triangular tube formed between the three clay slabs. The module was modelled in Rhinoceros 5 as a NURB entity of three double curved shells. In order to proceed with the simulation process in Ecotect, the structures had to be converted into mesh geometry and then simulated, thus angles of slabs and module overlap could be optimised.

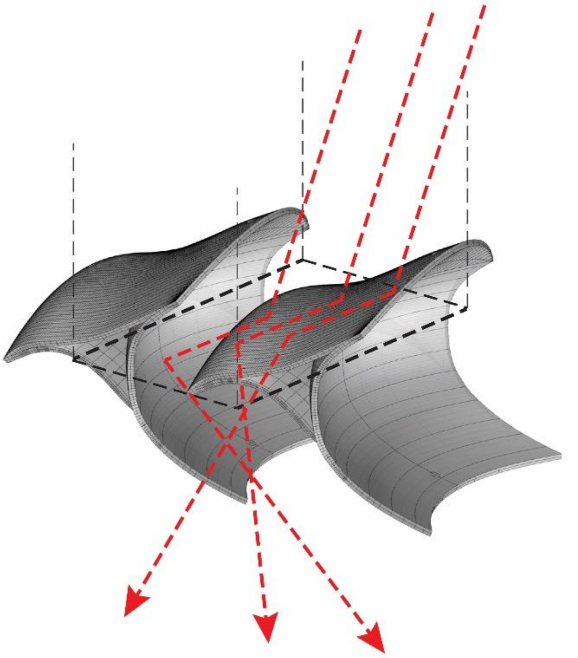


Figure 03: *Double curved louver unit and array with suspensive structure (black) and ray of light (red).*

In addition, slab formers had to be modelled as surface extrusion solids and exported as STL files, in order to be transferred to the CNC router (figure 4).

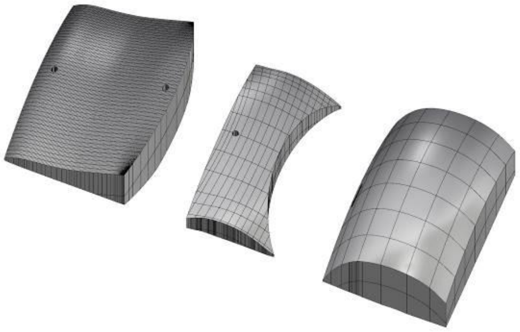


Figure 04*: Styrofoam formers 3D models for CNC production*

To fabricate the double curved geometry as a physical mock up model, each shell had to be unrolled into a planar 2D outline (figure 5). The flattened outlines were used as cut out stencils for the clay slabs. Once the three formers where finalised, each slab was then adjusted on them and then joined together forming the final component (figure 06). This proved to be a rather complicated process, related to the material properties of the wet clay, resulting different degrees of elasticity and formability according to the slabs thickness. Once the component was formed, it was left to dry before firing (Figure 07).

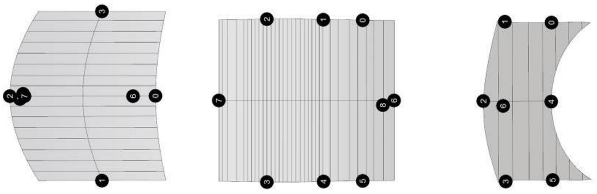


Figure05. *2D slab components*

Figure 06*: Forming the component out of clay slabs*
Figure 07*: Finalised ceramic component*

3.2. Layered Helix

The second design exploration should examine parametric / performative tools in combination with clay extrusion and CNC milling fabrication techniques.

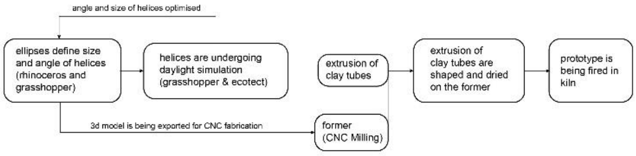


Figure 08*: File to factory process using clay extrusion*

As a consequence, the design component was conceived as a set of multi-layered helix louvers (a twisted extruded elliptical tube), which were expected to disrupt the direct light transmission from ceiling to floor. It was developed as a parametric Grasshopper model based on an array of ellipses, which were then lofted into a solid helix louver. Each ellipse can rotate parametrically around its centre allowing different degrees of curvature to occur, thus different qualities of light diffusion (figure 09). The Grasshopper script would define each ellipse out of four points and allow different radiuses for each. Other than Bechtold's radiance [11], the louvers were then connected to the Ecotect component, which allowed direct lighting analysis simulation of each helix in the Ecotect environment, but through Grasshopper.

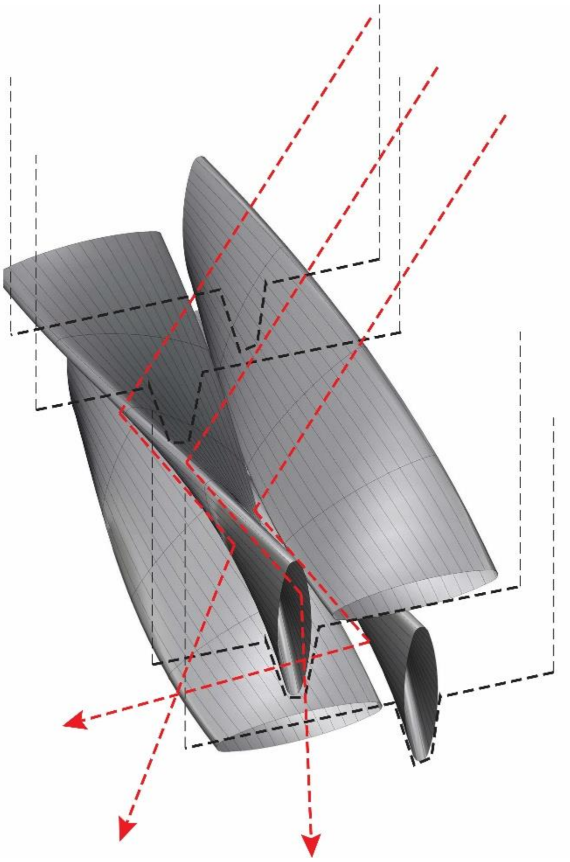


Figure 09*: Layered helices component with suspension mechanism (black) and ray of light pathway (red).*

Lighting simulation parameters, such as lighting calculation type, simulation precision and sky luminance could thus be altered directly in Grasshopper, within the 'Lighting Calculations' Geco plug-in component allowing direct optimisation of size, overlap and angle of helices.

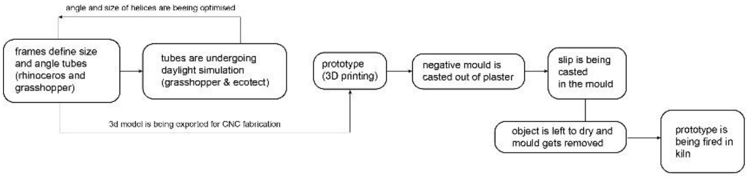
In addition, the optimised component was inverted into a negative 3D model, thus it could act as former, once it fabricated out of an STL file. In addition, an extrusion profile stencil was cut, out of the initial ellipse, thus the ceramic clay could be formed. The tube-like clay extrusions (figure 10) where then placed on the formers and left out to dry (figure 11), in order to be subsequently fired. The four helices would be assembled on a metallic framework, which would also enable their suspension from the ceiling.


Figure 10*: Unformed clay extrusions*


Figure 11*: Formed and dried helix*

3.3. Distorted Cone

The third design exploration is assessing parametric /performative design tools in combination with 3D printing and slip casting fabrication techniques (figure 12). The component was conceived as a distorted cone, which would re-direct light transmission according to the angle of distortion and the size of the upper side profile. Its complex geometry would allow no other fabrication method than 3D printing and slip casting. This component was designed as a parametric system in Grasshopper. It was developed as a parametric point grid system, where one cone was assigned to each grid point (figure 12).



*Fi**gure 12**: File to factory process, including 3D printing and slip casting*

Each cone was generated as a cone surface out of offsetted and distorted profiles (figure 13). Grid size and density, component height and distortion as well as the tectonics of the loft (e.g. soft edge, hard edge) could be modified and tested in terms of their lighting performance. The cones where connected to the Geco-Ecotect Grasshopper script as described previously, thus various angle, height and size of each cone could be simulated and optimised.

Once the required light defusing performance was achieved, the 3D-model was exported for 3D printing as an STL file. As soon as the model was printed, it was used as a prototype in order to produce a plaster-made mould, to be used for the remaining slip casting process, using a technique similar to the one described in the Digital Fabric research project by Vollen and Clifford [17]. In this case however, the negative mould was cast directly out of the 3D ‘Z-printed’ prototype. It was cast in two pieces; thus it could be opened easily in order to safely remove the final prototype. Ceramic slip, was then cast into the dried out plaster mould and poured out again 10-15 minutes later, in order to enable the creation of a thin ceramic slip layer (figure 14). After drying out, the finalised object was removed and the mould could be used again. Finally, all components were fired in the kiln. Assembly and suspension of all components is achieved through the use of a metallic frame-lattice, where each ceramic element can be placed.

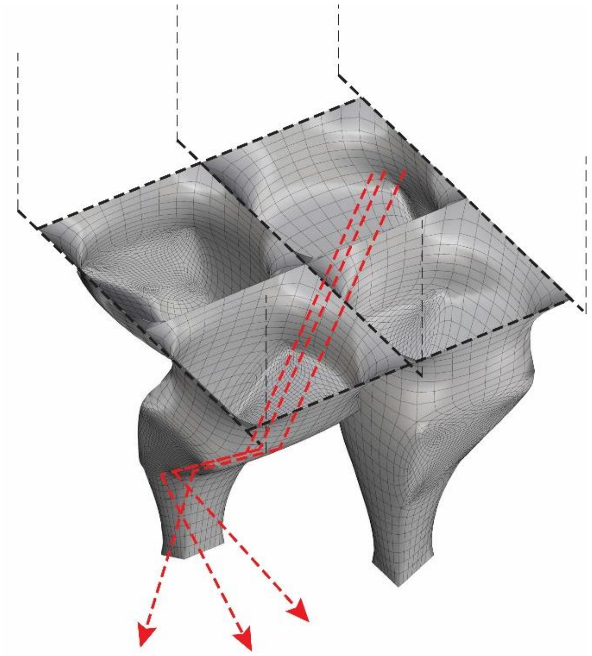


Figure 13: Parametric distorted cone units, suspension mechanism (black) and ray of light pathway (red).

Figure 14: Slip casting the cones out of clay slip

4. DISCUSSION AND CONCLUSION

Looking at all three different file-to-factory processes applied, one can clearly see the huge potential arising out of the combination of digital tools and ceramic crafting methods. The Combination of slab forming /extruding and CNC milling as well as slip casting and 3D printing appears to be well functioning fabrication paths, allowing formal expression enriched with performative properties. Similar to timber structures [14], the joint venture of digital technology and crafting is able to enrich the final product with formal complexity alongside performance, qualities often abandoned in serial production in favour of simplicity.

Innovative solutions did emerge. All three product prototypes did fulfil the pre-set criteria of performance (light diffusion), materiality (ceramic) and nonstandard form. In that sense, all three experimentations accomplished their aim. Even though manual crafting was largely involved in all three cases, one could incorporate these techniques in a fully automatized fabrication process, as described by Andreati S, Castillo J, Jyoti A, King N, Bechtold M [11].

In addition, looking into the detailed production flow, more findings occurred during the process, which are worth to be discussed. While 3D printing, as applied by Bechtold [10] or Sabin, Miller, Cassab, Lucia [6], is replacing ceramic crafting entirely since it is forming the product from scratch, the method used in our third experimentation incorporating 3D printing and slip casting, offers a useful alternative. The extraordinary elegance of the thin clay slip is a property, which has not been achieved in a 3D printing, additive process yet.

On the other hand, there are also findings which demonstrate the limitations of all three production methods applied. By looking into technical, process based details on all three experimentations findings vary.

In particular, starting with the first design exploration, the relation of form and fabrication technique used appears to be crucial. The unit's design was too complex to be fabricated using slab forming efficiently. The actual clay slabs were less elastic than assumed, and assembling the three slabs into one component proved to be difficult. During the drying process, cracks occurred on many of the components and they had to be remodelled. The final product was lacking precision and its sharp shaped surfaces could not be reproduced sufficiently. However, it is a valid fabrication method for simpler components, made out of one shell only, thus not requiring assembly with other slabs. The double curved louver unit would have been more easily fabricated by using a 3D printed prototype in combination with the slip casting technique.

The lacking parametrisation of the initial 3D model used, made feedback from the lighting simulation slower, demanding more time to re-inform and optimise it, according to its performance. The component's complexity made lighting simulation very slow and energy consuming, delaying the entire fabrication process even further.

The second exploration focusing on a combination of CNC produced formers and ceramic clay extrusion techniques, proved to be a very sufficient fabrication method. The tubular extrusions could be produced fast and easily. Their drying process was completed without the occurrence of any cracks. Producing the formers was inexpensive and they could be reused, allowing a high degree of production efficiency, consistent quality and a high precision output. A combination of variable formers and standardised extrusions, and mass customised components appears to be a possible path for further assessment.

By combining the parametric helices model with the Grasshopper /Ecotect simulation engine, interaction between form and performance was made possible, which made the optimisation process easier. However, simulating larger surfaces, made out of component clusters, proved to be difficult. It is a time consuming simulation process, thus actual interaction between form and performance appeared to be problematic. In addition, Grasshopper files had to become overcomplicated in order to achieve a sufficient simulation.

Finally, the third design exploration's fabrication process appears to be the most suitable for complex forms, allowing an almost perfect reproduction of the initial 3D object, without having to compromise in geometrical complexity. Furthermore, once the slip cast replica is removed from the mould, it can be re-used infinite times, making the object's customisation easy (Figure 14). However, casting a mould is a time consuming process and would probably make mass customisation difficult. In addition, considering the higher cost of the 3D printed prototype, it proved to be the most expensive fabrication technique, compared to the other two.

Looking at the bigger picture, including all three different production methods, the huge potential in incorporating digital design and fabrication techniques into conventional ceramic fabrication process becomes clear. Parametrisation and simulation software allowed design and fabrication of performative components and seems to enable unlimited formal expression. Clay and its property of unlimited plasticity used in a digitalised, performative file to factory process, offers a huge potential in ceramic component innovation. By understanding more of its material properties, the firing process as well as the various glassing coatings, further optimisation could take place. Additional parameters could be embedded in the design process; thus many more possibilities be explored in the future.

Figure 15*: Finalised array of cones after firing*

5. ACNKOWLEDGMENTS

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