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# Innovations in the production of ceramic luminous environments: where craftsman meets computer

## *Innovaciones en la producción de ambientes lumínicos cerámicos: entre técnicas artesanales y procesos digitales*

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ABSTRACT

Ceramics offer exceptional properties as an energy-efficient building material, but have rarely been investigated alongside active environmental performance. Responding to light-control criteria, we work with advanced digital modelling, fabrication and performance simulation tools to craft experimental full-scale ceramic prototypes of architectural daylighting components. Our research has three main goals: to investigate alternative daylighting technology solutions made of a low-impact material such as clay; to explore design methodologies that look into how current architectural ceramics manufacturing can be enhanced by emergent design and fabrication technologies; and to engage with the materiality of the clay through collaborative working with recognised artists and ceramicists. A critical aspect of our research is to test the compatibility and interoperability of different software and design techniques, as phases of the production process (optimisation of form finding) in real time. This paper presents the development, construction and analytical data of three of the experimental production methods developed during the first three years of this project.

**Keywords:** architectural components; ceramics; digital fabrication; daylighting; craftsmanship.

*RESUMEN*

*El material cerámico ofrece excelentes oportunidades como material de construcción energéticamente eficiente, sin embargo sus propiedades se han investigado muy escasamente en combinación con un comportamiento medioambiental activo. Respondiendo a criterios de optimización de la iluminación natural, trabajamos con procesos paramétricos digitales de fabricación, así como con herramientas de simulación energética para confeccionar prototipos experimentales a escala real de componentes arquitectónicos cerámicos. Nuestra investigación tiene tres objetivos principales: explorar soluciones para la optimización en el uso de la luz natural fabricadas con un material de bajo impacto como la cerámica; investigar metodologías proyectuales que miren a cómo los procesos de producción arquitectónica cerámica actuales pueden mejorarse gracias a la incorporación de técnicas digitales de fabricación y diseño, y comprometernos con la materialidad de la cerámica a través de trabajo en colaboración con artistas y técnicas artesanales. Un aspecto crítico de nuestro trabajo es probar la compatibilidad e interoperabilidad de diferentes plataformas informáticas y técnicas de diseño como fases del proceso de producción (optimización de la búsqueda de forma) en tiempo real. Este artículo presenta el desarrollo, construcción y resultados analíticos de tres de los métodos de producción experimentados durante los tres primeros años de este proyecto.*

***Palabras clave:** componentes arquitectónicos; cerámica; fabricación digital; iluminación natural; artesanía.*

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## 1. INTRODUCTION

The optimisation of natural lighting in non-residential buildings is a design priority, since it means a critical reduction of the three main end-uses of these buildings' energy consumption: lighting, heating and cooling (1), (2). There are a wide variety of advanced daylighting technologies[1] to help to reduce electricity consumption, manage solar gains, and provide a well-distributed and healthy luminous environment (3), but most of the materials and processes involved in the development of these technologies have in turn a high embodied energy and exert a serious negative impact on our natural environment (4), (5). In consequence, the investigation of low-impact and less energy-intensive materials in the creation of sustainable daylighting technology becomes a fundamental design factor.

Ceramics offer a wealth of opportunities in this forum: a simple ceramic tile has an embodied energy of 2.50 MJ/kg, whereas aluminium, a typical material used in the production of facade technologies, has an embodied energy of 227 MJ/kg (6). In addition to this, clay as a material is biologically inert and does not 'off-gas' in its raw state or once matured through firing. Ceramics provide a number of relevant attributes as an energy efficient material: in addition to its thermal mass capacity and high evaporative cooling properties, the raw material is fully recyclable, very durable, abundant and easily available, and can be currently glazed with lead-free, non-toxic finishes. Furthermore, current advances on technical coatings equip earthen products with germicidal, self-cleaning, free volatile organic compounds, and pollution capturing properties (7), (8), (9) some of which can be incorporated in single-firing processes thereby further reducing the embodied energy.

There is currently a disconnection between architects and the scientific environments in which the existing daylighting technologies are developed and this is another important issue to address. Most architects are little engaged in the application of existing sustainable technology, are unaware of their diverse range of working principles, and when used, they are regarded as add-ons whose physical impositions have a negative aesthetic impact. In order to achieve environmental, conceptual and aesthetic integrated results, it is necessary to engage designers in a holistic design process, and in this respect clay offers a tactile gateway through which designers can experiment and re-engage with this process.

Whilst clay holds great potential in environmental terms, so too it holds great potential in a wider architectural context, offering a new-vernacular language for components which are made from 'on-site' materials and offer a site-responsive language which articulates cultural identity. In terms of structural and aesthetic potential, it has high compressive strength and is very plastic in form, properties that can be further explored in combination with the opportunities that current digital fabrication technology offers. This means that nowadays highly complex non-conventional ceramic forms can be created that would have been impossible to achieve in our recent past. Despite all these advantages, so far the use of ceramics in contemporary facades shows very few explorations to exploit these properties, which can be fascinatingly enhanced if combined with sunlight control. Traditional and contemporary proposals of ceramic lattice walls have investigated privacy and shading but very rarely have studied the optimisation of their daylighting and thermal performance[2].

Capitalising on the renewed interest in 'making' within the process of architectural education and the interest in ceramics as a building component, our work's scientific objectives are threefold:

*a*) to explore alternative daylighting technology solutions, by investigating the use of clay instead of aluminium, acrylic and glass (typical materials for this technology, and highly processed);

*b*) to develop a new design methodology that pursues the fusion between current ceramics manufacturing and emergent design and fabrication technologies. In this sense, a critical aspect of our research is to test the compatibility and interoperability of different software and design techniques as phases of the production process (optimisation of form finding) in real time;

*c*) to investigate a use of ceramics that:
- looks at its environmental potential for daylighting components that are developed and designed with digital tools, but which seek to engage with the materiality of the clay through working with recognised and respected artists and ceramicists. Through our design processes we are exploring the richness that emerges through collaborative working but also through the necessity of working with a time served craftsman. As such we have been seeking a holistic approach not only to the subject matter; namely sustainability, ceramics and digital design, but to design which engages the designer (architect), the maker (ceramicist) and the analyst (engineer) whereby we have contemplated not only the embodied energy, but the embodied identity.
- And through our working processes we are seeking to implant the notion and accessibility of use into the psyche of future architects and engineers that clay (beyond tiles and bricks) is a material that can be creatively deployed within the construction and realisation of an architectural commission.

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[1] Although the use of windows is the most common strategy to admit daylight into buildings, there are situations in which these need to be complemented with an additional system, what are called advanced daylighting technologies: 1) to bring deeper and more evenly distributed light in the room or building; 2) when solar exposure is limited, to collect light from unobstructed areas of the sky and redirect it inside the room; 3) to control solar heat gains; and 4) to avoid glare.

[2] Exceptional examples of ceramics with thermal control (evaporative cooling) are the BioSkin façade designed by Nikken Sekkei for the Sony Building in Tokyo in 2011, to mitigate the Urban Heat Island Effect, and the ceramic pillars of the Spanish Pavilion at EXPO 2008, in Zaragoza, designed by Francisco Mangado, to generate a cooler and more humid microclimate around the pavilion. There are several examples of terracotta brise-soleil systems (rods), such as the ones designed by Renzo Piano (Debis Tower in Berlin in 2000, New York Times Building in New York in 2007 and Central Saint Giles in London in 2010), and Sauerbruch-Hutton (Museum Brandhorst, Munich, 2008), but they don't optimise the distribution of light. The crated façade designed for the Martinet School (Cornella de Llobregat, 2010) designed by Mestura, the movable screen for the Nembro Library (Nembro, Italy, 2007) designed by Archea, and the louvre system developed by Martin Bechthold's research group at Harvard University are amongst the few projects that pursue ceramics with daylighting optimisation.

## 2. ANALYSIS OF THE EXPERIMENTAL FABRICATION PROCESSES

### 2.1. Brief

To address the above-mentioned questions, a collaborative research-led design initiative was launched in 2011, involving undergraduate and postgraduate students from the Liverpool School of Architecture. The works referenced in this paper have been produced over a 3-year period, providing the foundations for the Environmental Ceramics in Architecture Laboratory (ECALab). This research work forms part of the Network of Ceramic Tile Studies Departments founded by ASCER (Spanish Association of Ceramic Tile Manufacturers), with research foci in Germany, Spain, UK, and USA.

In the first year and within the *Illuminating Through Ceramics Programme* (ITC) (10), (11), the brief was open to any ceramic and light-control possibilities, as well as any building component (light-redirecting screens, light-pipes, chandeliers, louvre-systems….), and no digital design tool specification, providing explorations for thirteen designs. In the *Performative Ceramic Screens Programme* (PCS) (12), (13) in the following two years, the brief was tightly defined: the goal was to design a light-diffusing ceiling for museums, exploring the ceramic surface to generate a system that blocks direct light (UV radiation) and distributes light uniformly in the room, with illumination limits between 50-200 lux. To achieve light diffusion, we mostly worked with multiple reflection (forcing the light to bounce several times from one surface to another) and texture (combining specular and irregular surfaces). The light-diffusing ceramic screen was generated through addition or repetition of 3-dimensional 'tiles'. We worked on eighteen separate designs for the 3-dimensional tiles using Rhinoceros and Grasshopper, each providing five progressive iterations through design development, in order to analyse the relationship between form and lighting performance. All the tiles had the same surface area, 300 × 300 mm, basing the optimisation process on changes in section, texture and surface reflectance in order to get different lighting performances (Figures 1, 2). Tiles dimensions were based on restrictions imposed by our artificial sky and heliodon (in which we measured a scaled (1:2) slab of 6 tiles, 300 × 450 mm, to check our simulations were correctly set), and our kilns.

The lighting assignment was mostly focused on 2D ray-tracing assessment to optimise how light was controlled by the ceramic profile, and lighting distribution (lighting levels and daylight factor) in a hypothetical top lit exhibition room. The lighting simulation software was chosen based on quick form finding optimisation potential, rather than on validation of the lighting performance of the design solutions. For that, the most reliable and accurate software available is Radiance, which requires highly skilled and time consuming training and operation. The scope of the presented work was not to validate the ceramic daylighting systems, but to test a design methodology that should be considered a first stage in the design process. The designs with greater potential of becoming a commercialised product, will follow further research procedures in which their performance is validated via modelling and physical measurements (14), (15), (16).

The assignment also avoided the use of ancillary or additional technology (processed materials). Firstly, because we wanted to simplify our material palette to explore the potentials of clay, rather than combine it or hybridise it. Secondly because we don't have the luxury that other plastic materials have (i.e. concrete, plaster), since clay needs to be fired. This is why it would be inappropriate to investigate design options similar to materials like *Litracon* (concrete block with embedded fibre optics).

### 2.2. How do we sit in the global context of ceramic prototyping?

Whilst there is much research in digital platforms, making parametric surfaces and sculpting parametric spaces, we are using these technologies as vehicle for manufacture rather than just for the final artifact. We want to explore what benefits new rapid prototyping techniques can bring to the design process of ceramic building components and how these proposals can provide tangible solutions. Firstly, how digital optimisation techniques (parametrisation and environmental simulation) would inform the design process (17). Secondly, which qualities can be incorporated into traditional ceramic fabrication techniques such as slip casting, extruding, or slab forming by using CNC milling, CNC cutting and 3D printing technologies. And finally we question the role of the artisan in the fabrication process. Whilst there is much research within the field of emerging ceramics that question the role of crafts-based processes, we are searching for a synergy between traditional and progressive production techniques. It is this unison that remains widely unexplored. Within the nascent field of advanced ceramic components we have identified four different approaches to prototyping:

Hand caressed components

These are pieces which involve high levels of workmanship or risk (18), where components are made by craftsmen using their tacit knowledge, intuitive processes and traditional techniques, and which largely require little tooling or manufacturing processes. These are unlikely to be appropriate for large-scale architectural installations and these are less likely to be used for mass production because of timescales and cost, but have an inherent beauty and bridge the boundaries of installation art, sculpture and product design. Erwin Hauer's work on concrete screens is an example of this type of component, from which we took great inspiration (19). The Tessellating Hexagonal Curtain made under the ITC Programme follows the same principles.

Hand tooled components

These are ceramic pieces that are developed using a variety of processes and bridge digital and analog methods of production to generate the final forms. They may utilise CAD/CAM digital design alongside digital manufacturing techniques for making moulds or formers but they are still produced within varying realms of human guidance and need the use of the human hand to generate the finished form, which allows for the craftsman to interpret the requirements of each piece and therefore still involves high levels of workmanship at risk. The experimental ceramic processes used in Villa Nurbs and Urban Guerrilla follow this line of exploration, which has been very influential in our research (20), (21), (22). Examples within the PCS workshop would include the Cruciform Helix Surface and the Sinuous Cones Surface.

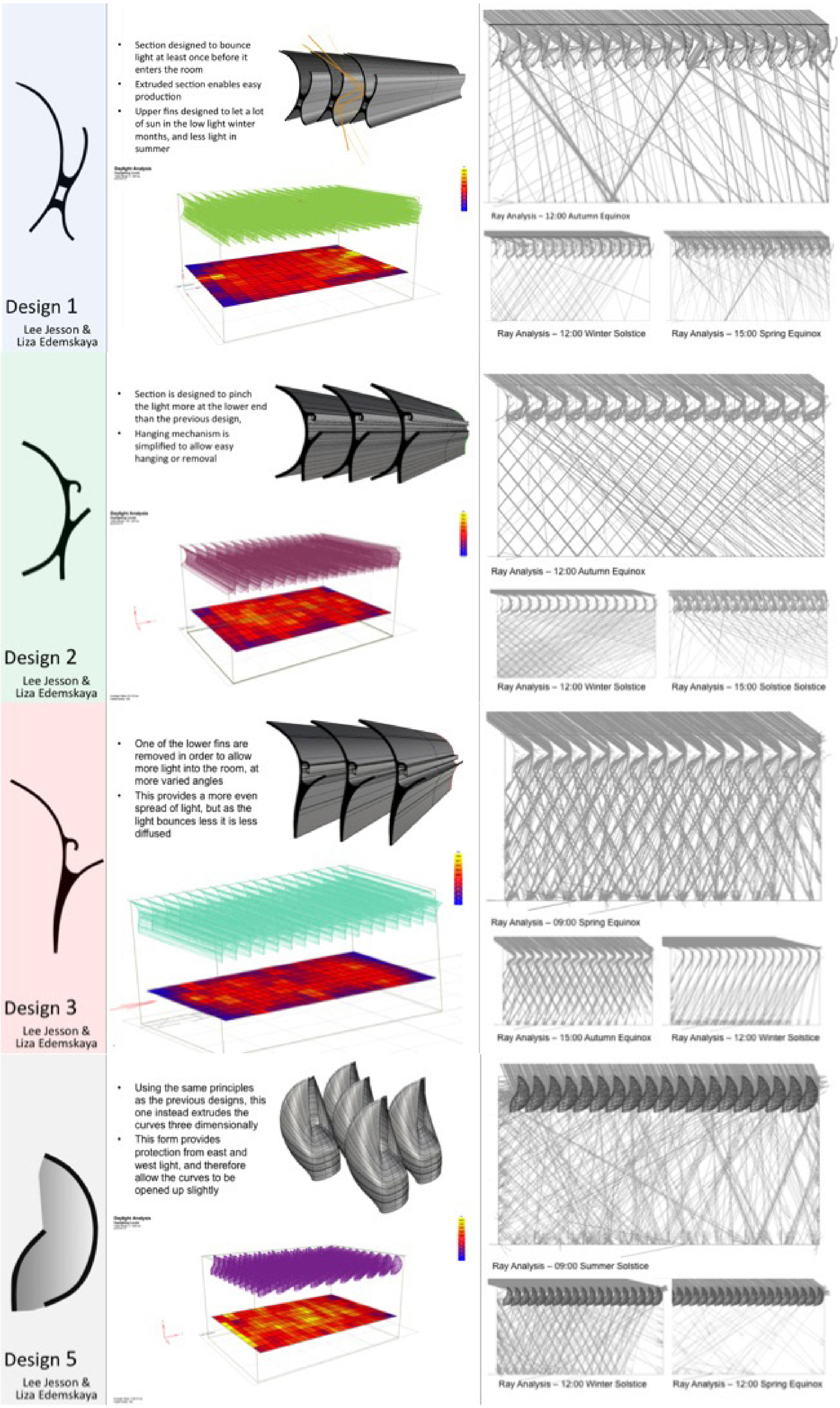


Figure 1. Example of 4 Iterations in a design optimisation process using Grasshopper – Ecotect/Geco.

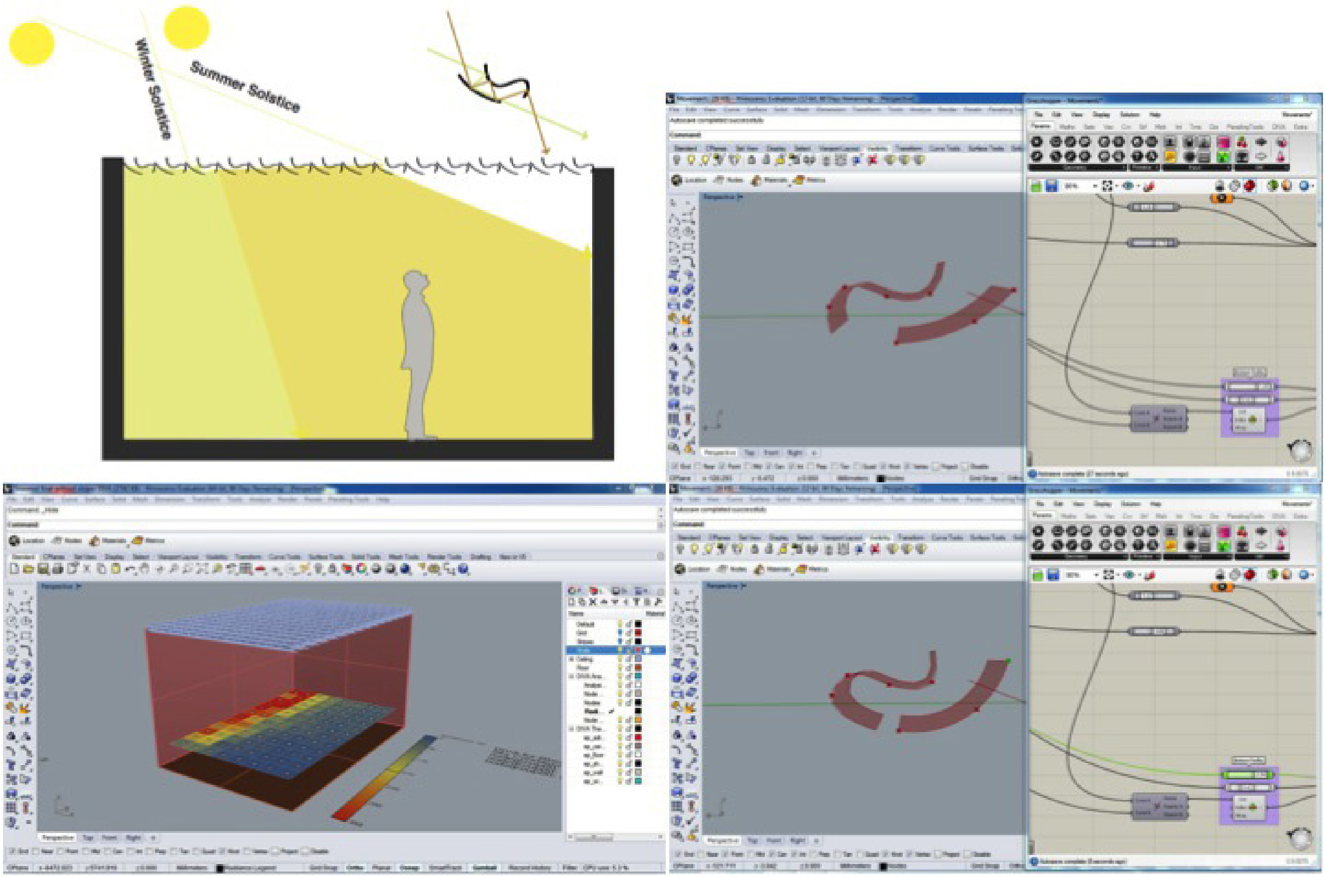


Figure 2. Example of 2 Iterations in a design optimisation process using Grasshopper –Diva.

Robotic tooled components

This is a file to factory process of realisation, which exports the digital design to robotic manufacturing machinery. Whilst there are different processes that sit within this production group, the products are mainly digitally translated with less necessity for analogue inputs. Where robotics are used to locate pre-made components the translated result will exhibit almost absolute workmanship of certainty (18). Where the robotic process involves the use of clay slip extruded as a coil through an automated nozzle, the product will retain an element of individualism and risk as it responds to environmental factors such as room temperature and relative humidity and complexity of the design which may need scaffolding to accommodate the sometimes unpredictability of the extruded clay slip and where each piece is susceptible to failure as the clay has its own life. Where the robotic process involves the robotic arm physically cutting rolled slabs of clay it still involves a great deal of workmanship of risk, as pieces are robotically cut before being formed by hand or thrown over CNC milled formers. Martin Bechthold's work on ceramic robotic fabrication and Gramazio & Kohler's research on the employment of industrial robots on the construction site exemplify this pioneering practice (23), (24).

Digitally automated components (3D printing)

This is a file to factory process of realisation, which is almost entirely beyond the control of the human hand. The design of these pieces will occur digitally and will be controlled through the 3d printing process to ensure that each piece produced is a facsimile of the one before. These pieces involve the highest levels of workmanship of certainty whereby a bed of powdered ceramic material is combined with a binding material that is laid down in layers and allows the production of very complex shapes as they are supported by the excess powder in the bed. Its limited commercial availability and high production costs mean that it is not a viable option for the production of building components at this time.

In this 3-year long process, we were interested to test the first two approaches, whereby we could bridge traditional skills and recognised manufacturing techniques with emerging technologies to generate components that can be mass-produced within the realm of current architectural practice. Essentially it is implicit in our methodology that our proposals are tangible, buildable and economically viable within today's world of construction by finding synergies between looking back at processes that have been perfected over many years[3], [4] and by looking forward at the potential of emerging

[3] Current industrial ceramics processes are dry-pressing, plastic-pressing, extrusion and slip casting. Innovative or alternative processes look into die-cutting, slump forming or moulding, 3-D printing, and ceramic foam. See (27).

[4] Existing industrial processes for customization (or craftsmanship) after the ceramic piece is fired include grinders, hydraulic cutters, disc cutters, sand blasters, laser, physical vapour deposition, kerajet (inkjet technology), tile folding, relief acquiring and milling. See (28).

**Table 1.** Parametric and environmental design and production methods experimented.

| Case Study | Digital Modelling | Lighting Performance | Fabrication |
|---|---|---|---|
| Tessellating Hexagonal Curtain | AutoCAD/SketchUp | Ecotect | Hand Building |
| Cruciform Helix Surface | Rhinoceros - Grasshopper | Grasshopper - Geco -Ecotect | CNC Milling, Laser Cutting, Extrusion, Extrusion Forming and Hand Throwing |
| Sinuous Cone Surface | Rhinoceros - Grasshopper | Grasshopper - DIVA | CNC Milling, 3D Printing, Slip Casting |

opportunities. The process should enable a feedback loop, thus potential findings during the process could inform the initial starting point.

Out of the thirty one generated designs, in this article we are presenting three of them, to discuss three different production methods in particular: one derived from the first approach, and two derived from the second approach, as illustrated in Table 1. The design methodology was supported by a design feedback loop that involved two different digital environments: firstly, using a software that allowed us to parametrically create the three dimensional drawings that represented the ceramic designs; secondly, these designs needed to be exported to an environmental simulation programme to test lighting performance, whose data would inform again the design of the ceramic profiles.

The three showcased production methods consider existing processes in a new way, and are successful for different reasons, having elements that we can capitalise on or develop further. Understanding the opportunities of these elements is what will give us new iterations in the future.

## 3. PROTOTYPES

### 3.1. Tessellating hexagonal curtain

Twenty-eight rotating and sliding planar hexagons compose the Tessellating Hexagonal Curtain. Alternating vertical alignments of hexagons, which are connected to vertical metal bars using a revolving fixing, form the vertical daylighting curtain. Each column of hexagons is independent, and suspended from a rail that runs along the entire glazing, allowing its movement and therefore the provision of shade or daylight by concentrating or spacing apart these elements in a particular area of the glazing. This horizontal flexibility in conjunction with the rotational movement of the hexagonal pieces allow for a plastic and fine modulation of the natural illumination.

This is a planar, geometrically simple component, which did not require parametrisation. The module was modelled in SketchUp and then exported to Ecotect, where different size, opening, and spacing variations were simulated. For a south oriented façade, the screen allowed a distribution of light from 1,500 lux next to the window, to 350 lux at 6 metres away from the window, when the screen is fully open (hexagons at 90°), at 12.00 pm on 21st June, to check performance as a shading device in the worst case scenario (Figure 3).

The ceramic hexagons (300 mm diameter) were made following a stratification process in which the delicate layers of porcelain clay show a heterogeneous internal porous structure that permits the differential transmission of light. Each hexagon was made using a 'slip' of porcelain paper clay and fine molochite, which was poured onto a set of specially formed plaster batts. Each piece was individually painted using locally sourced minerals before combustible materials were added to generate a pattern of texture and forms that passes along the curtain. Before bisque firing, non-combustible materials were added and textures imprinted into the surface and each of the individual slabs were rolled to the correct thickness. The hexagons were then cut from these three dimensional canvasses and the 'reclaim' was carefully configured to make new canvases which act as visual connecting pieces between the hexagons. The pieces were bisque fired at 1,240 °C before more glaze and glass were added and re-fired at the same temperature (Figure 4).

The optimsation process using this combination of digital environments led to clear conclusions. The lack of parametrisation in the initial 3D model made feedback from the lighting simulation slower, demanding more time to re-inform and

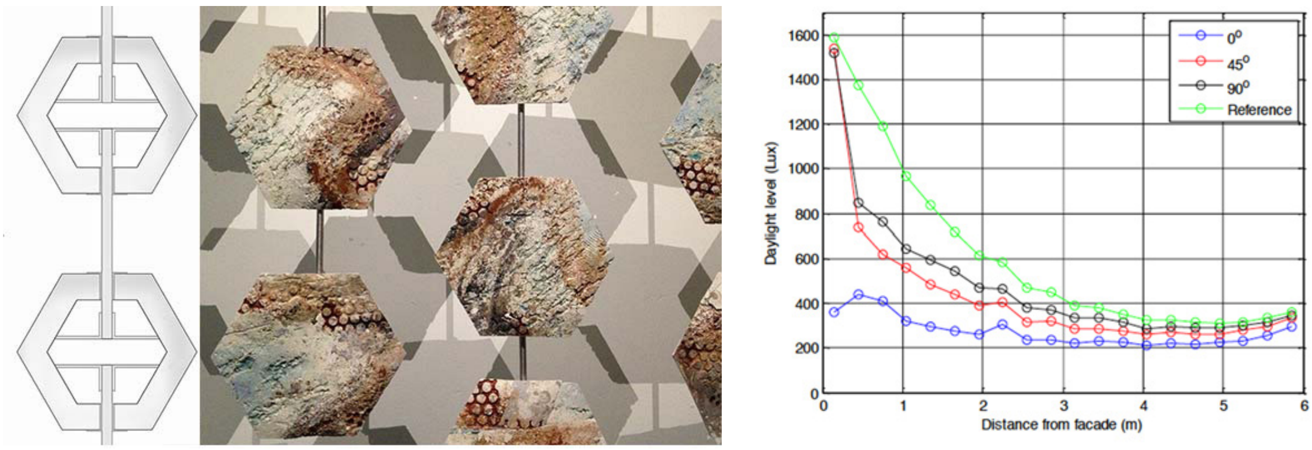


Figure 3. Left: CAD drawing and final ceramic pieces for the Tessellating Hexagonal Curtain. Right: Graph showing illuminance in relation to distance from the façade for 3 simulated rotated angles (0°, 45° and 90°).

Figure 4. Production process for the Tessellating Hexagonal Curtain ceramic components.

optimise it, according to its performance. The more complex the component the more RAM and time demanding the lighting simulation is, delaying the entire fabrication process even further. Ecotect was especially useful for ray-tracing and light pattern visualisations, in particular to detect the light-redirecting effect of some designs, but the software did not cope well with importing complex geometries, and required multiple attempts to get the simulations running. In this instance, the ceramic pieces were designed and fabricated in isolation and independent to each other without the benefit of the feedback loop. Conversely, the superiority of the craftsmanship is evident in each piece because of the level of freedom and interpretation which was given to the ceramicist and as such this process generated ceramic pieces that function as design solutions but also embody the sculptural principles of the ceramicists working practice.

### 3.2. Cruciform helix surface

This is a proposal whose individual forms are simple and elegant but achieve environmental success through their cruciform tessellating arrangement. Each of the components is made up of four elliptically profiled louvers, which twist through 90° along their central axis, creating a deep-layered surface that would scatter the ingress of light from ceiling towards the interior room. These profiles were developed as a parametric Grasshopper model, and then connected to the Geco-Ecotect component, which allowed direct lighting analysis simulation of each tile in the Ecotect environment (Figure 5). Lighting simulation parameters, such as accuracy/refinement, sky illuminance, type of simulation (lighting levels, daylight factor), etc. could thus be directly altered in Grasshopper, within the 'Lighting Calculations' Geco component, permitting direct interaction between geometry and performance analysis. The ceiling proved to successfully control light throughout the year except for the worst-case scenario at summer solstice with a clear sunny sky, where a repetitive light pattern can be seen across the floor with lighting levels ranging from 400-80 lux (average 300 lux).

Further optimisation of the ceiling or extra solar protection would be needed to control any excess of light in that period

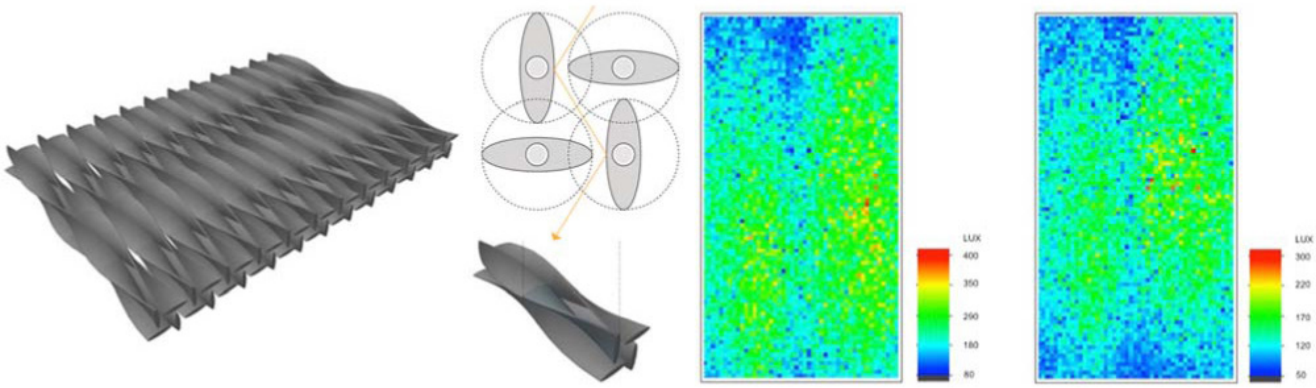


Figure 5. Above: 3D model of the Cruciform Helix Surface and sectional ray-tracing diagram. Below: Lighting performance of the Cruciform Helix Surface for extremes of worst-case scenario: Liverpool, sunny sky, 12.00 pm, 21st June (left) and 21st December (right).

(considering the recommended upper light level for exhibitions 200 lux). At winter solstice with a clear sunny sky we see a similar repetitive pattern and the lighting levels within the space range 50-300 lux with an average of 160 lux. This prototype has the added benefit of changing the spacing of each structural centre to allow more or less light penetration and diffusion depending upon the climate or region.

The pieces would have been suitable for 3D printing and slip casting, but this would generate a detail that would call upon additional structure within the piece during hanging, and wherever possible we expected the ceramic component to have its structure engineered into its design. Due to the simplicity of the elliptical profile it was decided that the most effective way to make the piece would be to extrude the section through a manual gravity fed extruder. The die for the elliptical profile of the louver was laser cut from 10 mm thick acrylic. Giving the correct shape to the extruded profiles called for innovations in the way that the clay was processed and as such a former was developed which allowed for the physical hand manipulation of the piece when the extruded clay is carefully thrown onto a former. For the 1:2 scaled prototypes, testing was carried out using CNC milled polystyrene formers, but these formers were deemed inadequate because of the induced differential shrinkage and cracking caused in the thin profile forms by the polystyrene which was impenetrable to moisture. We also noted difficulties in locating the central axis of the twisting form through which to locate the hanging structure. As such the profile was refined to accommodate the location of the bar and the anticipated shrinkage of the clay in the final full-scaled pieces. Kiln formers to support the full-scale ceramic pieces were made by a mix of file-to-factory processes and traditional processes. Shrinkage and over-sizing was a particularly important consideration in this fabrication process as the formers and the louvers would shrink differentially to between 10-15% of their fabrication size at different points within the process. The former shapes were milled from polystyrene using the CNC router. These polystyrene objects were then used to make 3-part plaster slip-cast moulds, from which clay slip formers were fabricated. This slip casting process is fully described within section 3.3, which follows. This process was repeated 30 times in order to make 30 plaster slip cast moulds for 30 louvers.

An earthstone ES10 extra smooth stoneware clay was chosen to make the 8 × 40 cm louvers. The clay was wedged thoroughly to remove any air bubbles within the clay. Through testing and prototyping this was found to be one of the major concerns during manufacture as small air bubbles cause imperfections in the surface of the louver as the edges are dragged through the extrusion die. As the clay was forced through the extruder the clay was left to hang to keep the piece as straight as possible whilst the structural hanging axis was located. Oversized extruded lengths were then cut, and carefully hand manipulated to generate the 90° twist before they are carefully thrown onto the bisque fired formers. Any handling and tooling marks are highly visible on the surface of this simple form and as such many test pieces were discarded and the clay re-wedged in order to create lengths that were as smooth as possible. Once located on the bisque formers, the lengths of twisted clay were cut as an oversized length (to allow for shrinkage during drying and subsequent finishing of the elliptical face) and the structural bars were fully inserted along the central axis of the twisted clay lengths. The clay lengths were then left under plastic covers to dry very slowly to minimize the risk of unwanted warping until the clay was leather hard at which point the surfaces were cleaned with sponges, flexible metal kidneys and scalpels. The forming rods were then removed before the elliptical end of the louver length was finished with a rasp/surefoam tool to clean the edge back to allow it to sit flush with the edge of the bisque former. Once bone dry, the greenware form shrank by up to 5%, this took approximately of 4-5 days because of the thickness of the extrusion. The extruded louver and the bisque fired ceramic formers are then bisque fired together at 1,120 °C in an electric kiln to ensure consistency in the colour of the ceramic pieces. Although the clay body is stoneware, it was fired at a lower earthenware temperature in order to minimize any warping and shrinkage. The pre-fired formers supported the clay pieces in the kiln and minimized any further unwanted warping. The firing process took approximately 48 hours. The kiln temperature was slowly increased over a 24-hour period to minimize the risk of cracking and once it reached 1,120 °C it was gradually reduced over the following 24 hours. During this bisque firing process the clay expanded as it reached the quartz inversion stage. Once the clay has reached the dehydration stage the chemically combined water was driven off and the irreversible chemical changes had occurred, and when the piece had reached its vitrification point the pieces contracted together and so further shrinkage of both the former and the ceramic component occurred together.

Visual inspiration for this piece was to simulate the diffused light, which occurs when looking up towards the sky when underwater. As such surfaces that are designed to optimize light reflection and diffusion are finished with a high gloss glaze and the visible surface has an opalescent mother of pearl lustre over-glaze. (Figure 6). The composition of the clear glaze was made largely of standard Borax frit (50 %) and Ball clay (30 %) with high alkaline frit, and Cornish Stone (10 %). The powdered ingredients are mixed with water and sieved. The glaze was spray applied with a compressed air spray gun, in a single coat. Areas that touch the kiln shelf were cleaned by hand and the pieces were immediately placed into the ceramic oven (100 °C) for 15-20 minutes to heat the ceramic and bind the glaze to the porous ceramic surface before firing. When bone dry, the pieces were glaze fired at 1,080 °C without the need for a ceramic kiln former as the majority of the shrinkage and warping had already occurred. Once the pieces were glaze fired, the opalescent lustre over-glaze was applied with a soft sponge. This process demands a very light application of the lustre in order to achieve the delicate visual qualities and reflectance for the environmental performance. Once the lustre was applied, the pieces were fired for a third time at 750-800°.

Combining the parametric helix model with the Geco plug-in for Grasshopper, allowed for immediate connection between geometry and analysis. However, simulating larger surfaces made from component clusters proved to be difficult in terms of RAM and time demands, along with file operability. In this instance the ceramic pieces were both designed and fabricated through collaborative working with iterations tested and refined in the digital feedback loop. As a pedagogical process this was highly successful. It provided the opportunity to combine advanced skills in digital design, environmental design and simulation, and showed how ceramics can be incorporated into working practice. It also generated innovative ways of working with clay within this emerging field of research. However, whilst this was a highly valuable learning process, it exposed the inadequacies of 'a hand' that has not had the time to learn to experiment and work with a plastic material that illustrates every defect in the making process.

### 3.3. Sinuous cone surface

This design was conceived as an array of light-catching pipes that would conduct and scatter light into the room. As a fixed light-control device, light would be captured, redirected and released following the same path in a particular direction. To avoid the accumulation of light in one area of the room, all the sinuous cones were differently oriented, thus covering a wide range of angles of incidence at different times of the day. The three key parts of the design are the light-capturing opening, the light-conducting body, and the light-diffusing opening that will release the light in the room. The sinuous cone was designed as a parametric point grid system in Grasshopper, assigning one cone to each of the grid points. The cones were connected to the daylight component DIVA Grasshopper script (Figure 7). Modifications in terms of height, sinuosity, and boundary tectonics could be simulated and optimised to achieve the targeted lighting levels of diffused light. The ceiling proved to successfully control light throughout the year except for the worst-case scenario at summer solstice, where we can see a progressive distribution of light from the edges to the centre of the room, with lighting levels ranging from 400-100 lux (average 350 lux). At winter solstice with a clear sunny sky we see a similar pattern and the lighting levels within the space range 40-170 lux with an average of 95 lux. This indicates that further optimisation of the cone may be necessary to suit certain climates or regions to ensure adequate passive lighting levels, or the addition of extra solar protection. The 3D model of the cone was exported for 3D printing, and this 3D print was used to produce a multi part plaster slip cast mould. The 2-part plaster mould was made by placing the 3D printed cone in a timber formwork and half encasing the 3D print with clay to locate the plaster mould joint line. The location of the joint line is crucial as this will be visible after the pieces have been slip cast. The first part of the mould is then cast in plaster. The pouring hole was simple to locate due to the three-dimensional form, and this was positioned at the neck of the finished piece. Once the plaster was dry, the clay was removed so that the second part of the mould and its locating keys can be cast in plaster. Once the plaster mould has cured, any imperfection in the surface is smoothed before drying completely for minimum of 2 weeks to ensure that the plaster has adequately hardened.

Figure 6. Cruciform Helix Surface: extrusion, components in polystyrene formers, plaster mould for formers and final ceramic formers, and final glazed components.

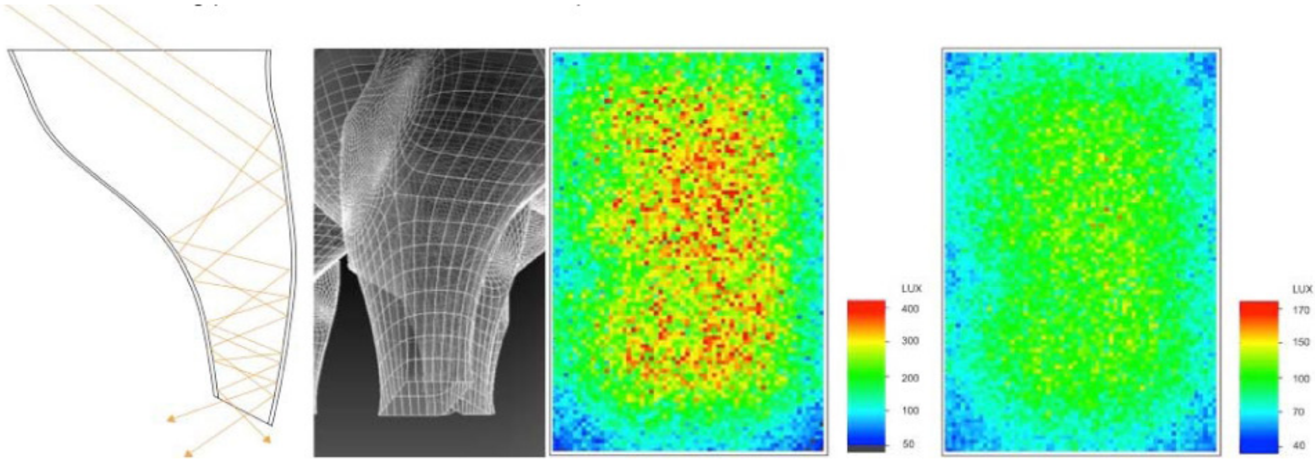


Figure 7. 3d model for the Sinuous Cones Surface with ray-tracing, and lighting performance for extremes of worst-case scenario: Liverpool, sunny sky, 12.00 pm, $21^{st}$ June (left) and $21^{st}$ December (right).

An earthenware clay body was used to prepare the slip by deflocculation. Semi porcelain clay, sodium silicate and soda ash were mixed with water to generate a slip to the desired viscosity. Trials were carried out to ascertain the casting timescales. Indoor air temperature, relative humidity, moisture content of the plaster and the shape of the form are key considerations when determining the timescales required. The clay slip was poured into the plaster mould and tamped to force air pockets out of the liquid clay. As the surface of the plaster absorbs the moisture, the level of the slip was re-filled as necessary. The clay slip was left for 30 minutes, before testing the wall thickness with a scalpel. Once the wall thickness of the piece reached 3-4 mm, the excess liquid slip was drained, and the greenware piece was left inside the mould to continue drying for a further 2 hours. After the clay object is removed from the mould the clay plug was removed from the neck and the base was carefully cut away to reveal the sinuous tube. Structural hanging points are then located with a piercing tool. The form was then left to dry until leather hard. The outer surface was finished and polished using a range of hand tools including scalpels, flexible metal kidneys and sponges (Figure 8). Once bone dry, the greenware form shrank by up to 5 %, and then shrank further within the kiln as the water between clay particles was driven off when the kiln reached the boiling point of water. The form was bisque fired at 1,120 °C in an electric kiln to ensure consistency in the colour of the ceramic pieces. The firing process took 48 hours. The kiln temperature was slowly increased over a 24-hour period to minimize the risk of cracking and once it reached 1,120 °C it was gradually reduced over the following 24 hours. When the piece reached its vitrification point the pieces contract and so further shrinkage of up to 10 % occurred. Overall once the sinuous cones had matured, they shrank by approximately 10-15 %.

The design of the form demanded that the inner surface of the sinuous form was highly reflective to conduct the light as indicated in the ray-tracing diagrams. This inner surface was clear glazed with a high gloss finish to achieve an index of reflectance of 0.92. The composition of the internal clear glaze was made largely of standard Borax frit (50 %) and Ball clay (30 %) with high alkaline frit, and Cornish Stone (10 %). The powdered ingredients were mixed with water and sieved. Due to the location of the glazed surfaces, the glaze could not be spray applied and so a single coat of glaze was manually poured into the interior of the forms, and areas that would touch the kiln shelf were cleaned by hand. The pieces were immediately placed into the ceramic oven at 100 °C for 15-20 minutes to heat the ceramic piece and bind the glaze to the porous ceramic surface before glaze firing. When bone dry, the pieces were glaze fired at 1,080 °C. The kiln was held at 1,080 °C for 15-20 minutes during the glaze firing before gradually reducing the temperature. A total of forty full-scale sinuous cone components (35 × 15 cm) were manufactured in order to generate a section of ceiling. This production method proved to be the most suitable for complex forms, allowing an almost perfect translation of the original 3D model. However, slip casting is a labour intensive and expensive method and resulted in a high percentage of failures during the glaze firing stage, but this method of production still proved more cost effective and time efficient in comparison to 3d printing in clay. The use of DIVA, in terms of appropriation and efficiency, revealed a very similar result as in the previous exercise: it was helpful as an optimisation tool operating within the same digital environment, but it is still a complicated, time consuming, and RAM demanding process. In addition to this, DIVA did not allow ray-tracing simulations. In this instance the ceramic pieces were designed through earlier collaborative working and then fabricated in isolation. The pieces were further developed prior to manufacture, and whilst the full scale pieces exhibit subtle developments to refine the light performance, incorporate installation requirements or change the form to make the component more suited to mass production techniques, the pieces do not embody the sculptural principles of the ceramicists' working practice as exhibited in the components made in the first exercise.

## 4. CONCLUSIONS

These projects highlighted a number of issues and opportunities in developing our understanding of working with clay as a sustainable material. It is important now for us to reflect on the processes and the lessons learned and the established manufacturing techniques that we have used and developed.

Through our adoption of digital technologies and testing of file to factory manufacturing techniques, we were able to design and test solutions in digital space, discard ineffectual designs at high speed and take forward just the key principles in a design feedback loop without the need to engage with

Figure 8. Sinuous Cones production process: 3-d print model, generation of plaster mould, and slip-casting to obtain the final ceramic pieces.

lengthy manufacturing processes. This embedded a desire for speed within our psyche and as such we expected all aspects of the workshop to perform to similar model of time and motion. Students were generating designs through Rhino and Grasshopper, simulating performance in Ecotect, Geco or Diva and then assessing and further refining the visual characteristics in the technical workshop and through the use of traditional tooling alongside laser cutters, 3D printers, CNC routers expanding the design feedback loop to bridge physical and digital platforms.

We assumed that we could employ this notion of speed to the production of the ceramic pieces, and whilst we were well equipped with CNC milled formers, 3D prints, laser cut templates, and laser cut dies, the material itself would not conform to our timescale demands, and it became obvious how the evolution of ceramic processes within the realm of traditional fabrication techniques casts aside any inappropriate use of the material.

Just as the pieces were tested digitally, we then went on to manually test the qualities of the clay body; its plasticity, its texture, colour, before testing the thickness, surface textures, drying times and firing requirements (we had a mix of earthernware, stoneware and porcelain prototypes in order to test different ceramic capabilities which need bisque to be fired at different temperatures.) Through testing, we ascertained that one cannot rush making the clay forms. If we aim to make products that are made by incorporating traditional construction techniques rather than a 3D printed version, then we must respect clay's nature. Ultimately hand making the object needs to heavily invest in personal time in order to build a set of baseline skills, because the clay will visually and technically expose any inadequacies of a hand that has not been given the time to learn and experiment with a material that illustrates every defect through the making process.

Through the testing process the lessons learned occurred mainly in the making of the greenware pieces and then the subsequent bisque firing stage. During the making stage, we regularly experienced shrinkage cracks. As the clay dries out it will usually shrink by around 5 % depending upon the clay body used and he firing temperatures. In traditional manufacturing techniques, plaster batts, moulds or formers would usually reduce the risk of differential surface drying and shrinkage crack as the plaster aims to absorb moisture from the underside of the clay at a similar rate to the air. But we were testing MDF laser cut moulds and CNC milled formers which were made from polystyrene and do not absorb moisture. Added to this, the relative humidity of the air was very low within the workshop and daytime temperatures were above average temperatures and regularly over 25 °C, which added to the speed of drying in the air facing surfaces. This was also evidenced where hand-built slabs were connected, and even though the same clay body was used to make the connecting slip, there was some differential drying. In the firing process the clay will expand and then rapidly contract to shrink by an additional 5-10 % shrinkage (5-15 % overall) and warping of the pieces was most evident in those that were hand built on formers.

This experience was in direct contrast to the pieces that were made as part of the ITC Programme. Many of the pieces here demanded surface texture and depth of clay profile for structural stability, and whilst the pieces were being fabricated at a similar time of year to those produced in the PCS Programme the country was experiencing an unusually wet summer in 2012, and precipitation was regularly above 5-10 hours per day, and as such the relative humidity and the air temperature hindered the production of the pieces as they took a number of weeks to dry sufficiently (to become bone dry) to minimize the risk of structural failure as the water expands and is forced out of the clay during the bisque firing process.

In terms of clay body, many students in the PCS Programme chose porcelain because of its inherent density, strength and whiteness, but as a clay body it is much less plastic than using extra smooth clay. It is also a time crucial clay body when the period of time between its wet malleable state and the point it starts to dry and shrink or crack is relatively short. As such projects using porcelain were much more susceptible to failure. By using extra smooth clay (where appropriate) as an alternative to porcelain and careful consideration of firing temperatures, we were able to minimize any visual implications and keep the fired clay as white as possible.

Students in the PCS Programme experimented by making moulds and formers through a number of different processes and whilst moulds can be used a number of times, these moulds must be allowed to adequately dry before its first use, this is up to 2 weeks, (we had not allowed for this timescale within the premise of the workshop) and then adequately dry between uses to ensure that they are rejuvenated and that the surfaces are not damaged as even small imperfections in the surface of the mould or areas of damage will be very obvious in the final finished pieces.

It is also worth mentioning the innovative active role that formers take for the Cruciform Helix Surface. Current industrial processes use polystyrene to produce three-dimensionally modelled and rapidly milled forms, but they are used as positives to produce moulds for slip casting (29), in the same way we used 3-D prints. Only some experimental practices already mentioned (Villa Nurbs and Urban Guerrilla) use polystyrene to produce formers, but we went a step further. Historically formers have been used as passive supporting devices. Within this process the former becomes an active element in shaping the ceramic component, becoming part of the design process: the straight extruded element is physically twisted along the profile of the former to generate the finished piece.

Whereas the majority of research in this area has focused on the two approaches to prototyping that most fully explore the use of digital tools as the primary means of fabrication, we have identified an investigation niche in which the hand of the artist holds an important role. For instance, 3D printing in ceramics is still not an appropriate commercial solution because of cost, timescales and size of pieces that can be created at present, and as such it was our desire to generate architectural proposals that can be incorporated into today's construction industry. With this in mind, the direction of our future research will be to revisit the haptic richness that we obtained in the ITC Programme, by engaging artists again throughout our processes. We intend to create fully interpreted pieces rather than objects translated from file to reality, in which the tangible qualities of ceramics cannot be fully exploited. We are searching for synergies between traditional and progressive production techniques that deliver plausible, buildable architectural ceramic components without losing the unique tectonic qualities of ceramics. We are currently working with a ceramic artist to investigate the surface qualities of tiled components to question how the artisan can be incorporated with a more cost effective and time efficient approach to produce a less cost prohibitive product through the innovative use of glazing techniques. (Figure 9). This will then reconsider the design loop by questioning how a product can be enriched rather than embellished with the integration of the artist from the outset. Further to this, we are in discussions with specialist coatings manufacturers to ascertain how environmental considerations can be further incorporated into this method of production.

When reflecting upon the process of optimisation, software capability to assimilate complex detailed surfaces, and software interoperability have proved to be crucial areas for improvement and potential development. Although architecture is embracing a position in which performativity becomes the design driver, the scrutiny of the current computer tools with which most of the professionals work actually reveals a paradoxical disconnection between geometry and analysis. That is, the computer decisively affects us, enabling the design of buildings from simulations and visualisations of processes in which we can even play with both planned and unpredictable situations, but we are still struggling to combine softwares in a single digital environment, in a way that we can simultaneously design architecture and understand the environmental implications of our decisions. Software interoperability remains a huge challenge, as a platform to exchange and compile information, and provide an accessible design framework not only for consultants and analysts, but also to any designer. In our coming projects we will explore the use of alternative separated software packages that include other environmental aspects, such as Design Builder; a comprehensive package that can do all the environmental analysis in one platform.

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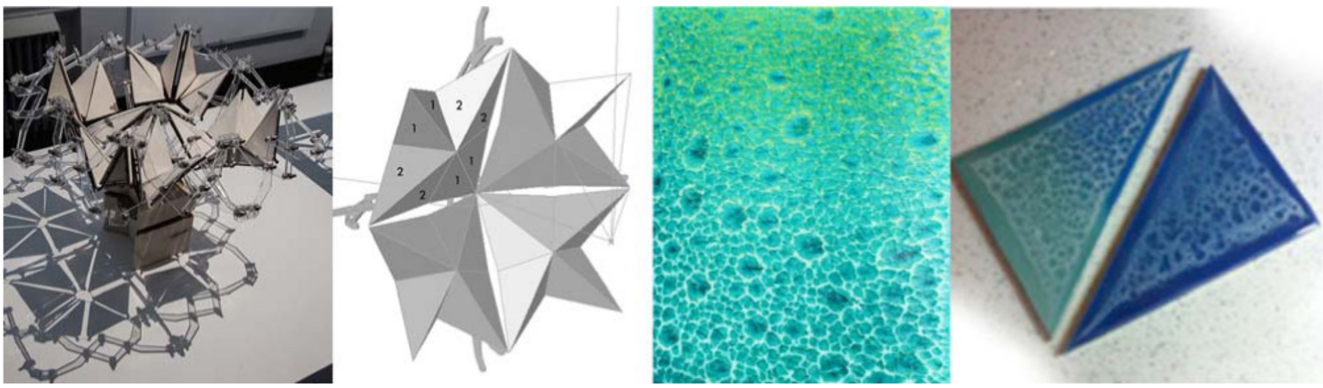

Figure 9. Glazing experiments with artist Wendy Lawrence for the ceramic actuators of a kinetic ceramic skin.

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