1.1. Research Overview

The research presented herein is an investigation into the use of functionally-graded (FGM, also known as multi-) materials in architectural design. Drawing from recent instances of graded material research in fields adjacent to architecture, it proposes a new CAD methodology of designing (a building envelope detail) with FGM.

1.2. Fused Materiality History

Fused materials have been used in the form of alloys since time immemorial but were only introduced in the form of gradients in the 1980s. Back then, Japanese researchers solved the problem of high stresses building up in the connection of metal to ceramic parts in hypersonic space planes, by developing a new type of (functionally-graded) material consisting of ceramic fusing into steel continuously in one volume (Figure 01). That way the thermal insulation properties of ceramics were combined with the structural properties of metal, eschewing the use of any mechanical fasteners or joining that would compromise the integrity of the material system.

1.3. Functionally Graded Materials in Architecture

Being discerned into two groups of surface and volume FGM[1], up until recently these materials ranged from micrometres to a few centimetres when manufactured in laboratories for research purposes, while their industrial application in larger volumes took place in specialized facilities and was detached from mainstream construction. However, according to Tom Wiscombe (2012, p.6):

> "the fabrication of multi-material matrices was extremely difficult and only cost-effective for the aerospace industry, and only in rare cases. It has involved making multiple forms and melting materials together under extreme conditions. Now, 3D printing has entered its next generation, where not only can multiple materials be deposited in micron layers at the same time but also gradient mixtures of these materials."

Furthermore, current recent research initiatives indicate that the transfer of the idea of graduating materials from fields such as aerospace engineering to the construction industry can enable energy and material savings, while eliminating the formation of weak points found in mechanically connected parts (Federal Institute for Research on Building, Urban Affairs and Spatial Development, 2011). Although not yet widespread, this multi-material paradigm is beginning to make its way into architecture, currently through the fabrication of small scale representational multi-materials, with research however, already conducted towards their wider application in the building industry in the near future (Federal Institute for Research on Building, Urban Affairs and Spatial Development, 2011; Oxman, Keating and Tsai, 2011).

1.4. Anticipated Impacts of Graded Material Application in Architecture

With all this in mind and in the context of a gradual shift towards the incorporation and application of graded materiality in architecture and design, it is logically envisaged that the following will be the fundamental changes occurring as a result:

a. Tectonic construction, based on the assemblage of materially uniform, discrete building components will be replaced by the continuous *fusion* of materials.
b. *Fusing* will become the appropriate building technique linked to this 21st century material paradigm.
c. Discrete boundaries will be replaced by *gradients* which, being more 'forgiving' than discrete components, will see the acceptable margin for error rise.
d. Designing and building will be made with materials directly.
e. There will be a shift towards a new design process in which material behaviour is prioritized.

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[1] For thin sections/surface coatings and for material volumes respectively. Designs in this research are concerned with the latter.

f. *Procedures of translation from 3D CAD information to 2D (drawn) instructions that are then converted into built space, will be superseded by seamlessness between designing and building.*
g. Principles of composition previously based on discrete geometric elements will be rethought.

1.5. Research Question

Effectively, the focus of this research is on points e., f., and g. (in 3.2.), while the main research question is, *what is the appropriate design methodology that can correspond to the use of functionally graded materials in architecture?*

1.6. Main Arguments

What is argued for in response, is that when the relevant technology eventually allows for direct one-to-one fabrication of the multi-material specified in the digital domain being the multi-material that is 3D-printed in full scale, the focus will shift from the design practice of "*drawing as an assembly of 'lineaments'* [emphasis added]" (Ingold, 2013, p.125) towards the one of *computational material "cooking in a bag* [emphasis added]" (Lynn, 2010, p.19). Correspondingly, a direct approach that integrates physical material properties as part of the design process will be critical. The designer's objective in this instance will be to generate a framework within which, materials are allowed to blend into continuously graded topologies. In effect, these can be summed up as:

- *Fusion* enables a novel way of designing directly with *liquid*, *mixable* matter in digitized form.
- The design process corresponding to this practice should be about establishing a framework and a set of relations, i.e. designing the circumstances, for form and gradients to emerge from material properties.

1.7. Design Objectives

The first objective in effect, is to formulate *a novel step-by-step methodology/workflow of designing with functionally-graded materials*. In terms of a specific focus, this procedure is targeted to the glass to aluminium frame connection in a unitised curtain wall and concerns the whole process from beginning to end, of research, design, and fabrication of the part. Effectively, a second objective is to *fabricate the redesigned connection in a physical multi-material*.

1.8. The Problems with Curtain Wall Systems

The reason for targeting this method towards the design of a curtain wall segment is the latter's association with a myriad of problems that mainly have to do with low environmental sustainability, redundancies and inefficiencies in the componentry supply chains and onsite installation, as well with the operational inadequacy and potential failure of the panelling after it has been installed. Indicatively, in terms of its environmental impact a typical "aluminium framed opaque insulated glazed curtain walling system" has the lowest C rating score in the categories of "climate change", "human toxicity to air and water", "eutrophication", "recycled input" and "recycled currently" (Anderson, 2009, p.36), as well as the same summary rating in the overall category average for cladding and framed construction. The sources of some of these problems can be pinpointed *a.* in the extraction and processing of the materials that the different subparts of a panel are made of, *b.* in the fabrication techniques of these parts, and *c.* in how the panels are procured, assembled and installed in a building.

Regarding point *b.* for instance, typical fabrication methods include low pressure die casting, injection moulding, anodizing, and powder coating. Low pressure die casting is used for manufacturing the aluminium components, which are then powder coated (for the mullions and transoms) or anodized (for parts such as the aluminium glazing lining). The process itself involves the pouring of molten material into a mould using low pressure gas. Apart from requiring high tooling costs[2] this "uses a great deal of energy to melt the alloys and maintain them at high temperatures for casting" (Thompson, 2007, p.127). Injection moulding, used in fabricating the EPDM, insulation bar, silicone

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[2] As "tools have to be made in steel to be able to withstand the temperature of the molten alloys" (Thompson, 2007, p.127).

gasket and glazing sealant modules, requires materials to be in high temperature and pressure, and again entails high tooling costs that “depend on the number of cavities and cores and the complexity of design” (Thompson, 2007, p.52). In addition, manual handling of the mould for preparation and for removing the parts has a further impact on cost increases. This is subsequently reflected in the fact that in terms of the costs involved, a curtain wall glazing system has the largest pound sterling to square metre ratio of all framed construction systems (Anderson, 2009).

1.9. Design Subject Specifications

Regarding the attributes of the panel, a segment of which will be redesigned, these have been set out in collaboration with a senior facade engineer at AKT II Envelopes and have also been input in the structural analyses that are presented in 2.10.7. More specifically, the main assumption is for a unitized curtain wall system installed on a rectilinear, mid to high-rise office building, in a typical central London location. The detail used in the design is model FW 50+SG from the Schüco Facade System catalogue, a standard, widely used off-the-shelf model. The aim of the design is to preserve the structural and optical qualities of the original panel.

1.10. Research Limitations

Due to the novelty of the subject of graded material design, a main limitation is that any precedents of historical value or any built examples are non-existent. In addition, although there is published literature in the form of research papers and proceedings books, it is of a scientific nature and to a very large extent inaccessible by a non-specialised audience. Furthermore, the design investigations that can be found in research and conference papers are equally technical in nature and in their majority concerned with custom CAD tool creation. This is due to the fundamental problem of the non-availability of graded information CAD software that one encounters when attempting to design with multi-materials in the computer.

1.11. The Current Paradigm of B-Rep Based Computer Aided Design

This is as computer aided design with gradient materials is something that does not yet exist in commercial software presently used in architecture. Existing software packages represent *volume and space through what is known as b-reps or boundary-representation-objects*, which are representations of the limits of a surface or volume within the digital environment. Complex forms are then constructed through cutting up and joining individual b-reps that when put together generate complex but hollow representations of what is the virtual equivalent of an envelope. Eventually, the way that digital representation of buildings or building segments is made, is through accumulations of these discrete elements that are stacked together like a kit of parts to create larger three-dimensional assemblies.

1.12. Voxel Design- Critique

The non-commercial, fringe method currently used by researchers in architecture that does incorporate graded information is voxel-based software. Voxels are volumetric data sets that are the three-dimensional equivalents of pixels used in digital images. A criticism posed of this method, however, is that actual material attributes are not considered. This is because these platforms concentrate primarily on the distribution, positioning and assigning of sub-materials in digital space, with a multi-materiality which nonetheless is of a representational nature as it is attributed as RGB colour values and not as digitised physical properties such as density, viscosity, surface tension etc. Additionally, the chemical compatibility between different substances to bond into larger multi-materials is another primary parameter that is not incorporated. In this respect, this research argues *against* the voxel-based static model of prescribed and representational sub-material distribution in which gradients are assigned through a 3D painting operation (which is what voxel design essentially does) and *for* the incorporation of physical properties.

1.13. Computational Fluid Dynamics- Particle System Elements

As fusion typically occurs in materials in their liquid state, the appropriate CAD method for the emulation of this phenomenon in the computer are computational fluid dynamics (CFD) simulations.

More specifically in this case, particle system elements (a CFD method) are by virtue of their computational structure made to simulate natural phenomena and effectively the behaviour of materials in their malleable state. They are therefore used to simulate the graded fusion of materials in the glazing to frame connection that will be presented in what follows.

1.14. Definition of Main Design Parameters

On this construal, there are three main parameters that affect the way liquids mix in a particle simulation. *Firstly*, the form of the mould that they are going to be contained or poured into. *Secondly*, the affecting forces or agency. *Thirdly*, their fusion compatibility, as non-chemically compatible substances can mix virtually, but cannot be fabricated physically.

1.15. Methodology Outline

The main steps of the corresponding epistemological framework for setting out, running and evaluating the results of the simulations are:

a. Identification of appropriate materials to be fused and verification of their chemical compatibility (this is performed by identifying manufactured FGM in material science literature).
b. Definition of the formal characteristics of the containing vessel (these are informed by naturally occurring dissimilar material attachment principles).
c. Calculation of the anticipated structural loads on the overall curtain wall panel (in collaboration with a facade engineer from AKT II).
d. Assigning of appropriate forces and computational agency in the simulation environment (these are informed by the types of forces employed in industrial FGM manufacturing and by structural load analyses).
e. Definition of criteria for terminating the simulation (this is performed by visually inspecting the gradient extents at each timeframe of the simulation and comparing these against the graded structure micro-characteristics defined by Miyamoto et al. (1999, p.41)).
f. Fabrication of expository artefacts for evaluating stages of the process model (in collaboration with Next Limit Technologies).

1.16. Design Studies Definition

Consequently, and in terms of the above-mentioned three parameters that need to be considered in designing fusion, the studies that follow are divided into two parts. These reframe and expand upon research published in Modelling Behaviour: Design Modelling Symposium 2015 (2015, pp.283-294). The first part, a precursor to the main design, consists of an investigation into the material consistency of an aluminium wind fence and aims to specify *a.* the material that can be ad-mixed to ameliorate its structural properties and *b.* the affecting agency parameters that will enable fusion. The purpose of this study is to establish the basic prerequisites for structuring a material simulation. The second part concerns the design of the curtain wall segment and deals with *a.* material type, *b.* mould characteristics, and *c.* force attribution.

2.1. Simulation & Reality

When describing their argument in favour of the epistemological dependence thesis[3] Norton and Suppe suggest that “a valid simulation is one in which certain formal relations (what they call ‘realization’) hold between a base model, the modelled physical system itself, and the computer running the algorithm” (Winsberg, 2009, p.840). Responding to this, Winsberg (2003, p.115) states that this “begs the question of whether or not, to what extent, and under what conditions, a simulation reliably mimics the physical system of interest.” As already mentioned, simulations here are utilised for design rather than scientific purposes. What can be therefore argued in response, is that the endeavour in what follows has been for these formal relations to be present in the form of assigned simulation parameters resembling physical material properties and values as closely as possible, and

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[3] According to which the degree to which simulations can be valid, depends on the degree of their resemblance to experiments.

of the simulation forces being informed by FGM manufacturing methods and by the loads acting on a multi-material segment of a larger overall topology. As it will be discussed, however, in some instances of FGM industrial manufacturing materials are structured against their natural propensity to self-arrange and fuse.

2.2. Accumulative Roll Bonding Multi-Material Manufacturing

In terms of the industrial manufacturing methods, according to Schmidt et al. (2012, p.1009) “graded materials [can be manufactured] by particle reinforcement during accumulative roll bonding”. This method consists of aluminium sheets sprayed with an aqueous solution consisting of copper particles at 33.3% concentration with an incremental feed velocity and distance from one end to the other. The sheets are then roll bonded together recursively, generating a ‘sandwich’ material consisting of copper particles gradually compressed within the aluminium matrix. The advantage of this technique is that the tensile strength of the aluminium sheet is increased, which is “proven by tensile tests showing a steady and monotonous gradient along the rolling direction” (Schmidt, et al., 2012, p.1009). This also means that the copper particle gradient can be deliberately distributed in a manner that can be “directly opposed to the gradient in loading condition” (Schmidt, et al., 2012, p.1009), in effect having a direct impact on the structural performance and amount of material used in the sheet.

2.3. Design Study 01- Definition and Material Selection

As the intent here is to define a model that simulates real world material gradients, the selection of materials in this case is determined by their existence as a physical multi-material entity. The technique by Schmidt et al. (2012) verifies that aluminium and copper bi-materials do exist physically[4], and the two substances are therefore utilised to design a panel hypothetically exposed to a high wind speed condition.

2.3.1. Design Study 01- Objectives

In effect, a first objective is to decrease the overall amount of material in comparison to a conventional aluminium panel. A second objective is to allow for openings on the surface of the sheet that would cover approximately 25% of the total surface area[5] (Government of Saskatchewan, 2016). This is in order to partially allow wind through the element and minimise turbulence right behind it in the case of it being completely solid. Primarily, however, the main objective is to answer point *b.* and to establish the appropriate forces (or affecting agency) that should be employed in a material blending simulation.

Starting the design process off, a direct frontal wind was simulated for velocities of 90 km/h with the generated pressure map indicating the load distribution on the surface of the sheet (measured in Pascal units). Regarding the blending simulation, the Liquid Temperature for copper was set to 1200 centigrade (1473 Kelvin) and for aluminium to 660 centigrade (933 Kelvin), both slightly above the melting points of the materials. Their density and viscosity were also attributed: copper at 1200 degrees centigrade has a density of 7,898 kg/m³ and dynamic viscosity of 0.00312 Pa·s, while for aluminium the values are 2,375 kg/m³ for density and 0.001379 Pa·s for dynamic viscosity.

2.3.2. Agency Informed by Accumulative Roll Bonding

In terms of the *affecting agency*, the principle likewise was for it to be informed by forces that would affect the material physically, with one being the standard gravitational force of 9.8 m/s^2. The other force attributed was a Limbo daemon[6] that consisted of two notional horizontal planes that constrain the movement of particles in the space in-between. This was used in this case in order to bear a

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[4] This is also the case in aluminium bronze alloys that are mixtures of aluminium and copper.

[5] This figure derives from the fact that the panel’s use is in an industrial type wind fence that is typically deployed in sites of very high wind speeds, with some of its functions being among others to prevent soil erosion, reduce wind loads on sensitive components and prevent the dissipation of stored material at exposed industrial sites. Consisting of aluminium or steel parts, the clad material of the wall system needs to be porous in order to partially allow wind through the structure, avoiding that way any turbulence caused as a result of it being completely solid.

[6] A daemon is essentially an external force that can be input in the simulation environment that can affect the particles within its field of influence.

closer resemblance to the manufactured sheet that had the copper particle reinforcement horizontally spread across the middle of the aluminium body. The first simulation was eventually set out with three aluminium and one copper particle emitters placed within a container and allowed to run until the copper accumulated horizontally across the centre of the aluminium matrix in a gradient manner.

2.3.3. Design Study 01- Evaluation of Result

According to research by Schmidt et al. (2011), the tensile strength of commercial purity aluminium (≥ 99.5%), which is 75 MPa was increased to 160 MPa when copper of volume fraction of up to 2.9% was added to it, effectively enabling an approximate increase in tensile strength of 53%. In this case the structural objective would be attained as it is foreseen that the tensile strength increase from the bottom of the sheet and towards the top that measured 2,000mm in total, would range in percentage according to copper content, with an average being the aforementioned 53%.

2.3.4. Design Study 01- Agency Critique

An observation at this point was that the force assigned in this first exercise could not exist physically. More specifically, the attributed agency was made to act selectively on some of the materials, while leaving the rest of the substances unaffected. Physically speaking this can happen with magnetic forces that only have an influence on ferrous substances. Regarding the Limbo daemon, however, and following extensive research on FGM manufacturing techniques there was no evidence of the physical existence of any type of force resembling it. It was therefore assumed at this stage that its use would be counter to the objective of bridging the physical and virtual domains.

2.4. Non-Invasive versus Contact Forces

In addition, it could be argued that the accumulative roll bonding process described above also goes against the main argument in 1.6. of allowing fusion and gradients to emerge from material properties. This is because roll bonding involves a forceful, severe plastic deformation processing of materials that is contrary to the required *non-invasiveness* of agency in a simulation[7].

In addition, the basic acceptable force that requires no justification for its application on a material is gravity. Placing any other *non-contact force* in a simulation environment can either derive from an analysis of the structural loads acting on a larger multi-material topology, or from the loads employed in manufacturing FGM. Using the computer to accelerate the effects of these loads on matter, in effect the output would be an arrangement of sub-materials in a multi-material that draws and corresponds directly to physical world conditions.

An example of these loads is the wind pressure on the aluminium sheet. The wind first applies force at the centre of the panel and is then deflected upwards and at the back of the sheet, generating a tensile force that is exerted against gravitational pull. This effect can be represented in a quite straight forward manner in a digital simulation through a *negative attraction* or *vortex daemon*.

2.5. Agency Informed by Loading Conditions

A second simulation was therefore run in which the gravity force was maintained, and the Limbo force applied in the first simulation discarded. In its place and in addition to gravity, the aforementioned vortical force generated a centrifugal-like pull at top end of the container in which the digital materials were poured. Here, it should also be mentioned that apart from the tensile loading, another parameter that informed its use in the first place (as well as its magnitude) was the industrial casting method for the creation of continuously graded FGM described by Watanabe and Sato (2011). This method involves a preheated spinning mould containing solid particles of material A, in which molten material B is poured. The centrifugal force generated during spinning separates the two materials at the opposite ends of the mould and a gradient is formed between them due to the difference in their respective densities.

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[7] In this case the term *invasive* equates to any physical apparatus that coerces and imposes form on materiality, cancelling out the intrinsic chemical-bonding capability that materials have when blending together under centrifugal, gravitational, magnetic and other *non-contact* forces.

2.6. Design Study 01- Evaluation

Consequently, placed under the influence of the vortical agency, the copper particles were distributed across a region similar to the pressure area on the panel that was derived from the wind simulation. The resulting multi-material sheet was 100% copper at the bottom and 100% aluminium at the top with the middle region consisting of copper in front, aluminium at the back and a gradient formed in-between. The total area of the openings (approximately 23%) was close to the objective of 25% (Figure 02). Corresponding much more closely to the loading condition on the panel but with a partially different composition to the layering of the roll bonded sheet, further studies would need to be conducted in order to verify that this material arrangement has the same, or similar tensile behaviour to the sheet produced by Schmidt et al. (2011). Having said that, the main point of this study was to illustrate through a practical investigation the forces that should be employed in a blending simulation, in response to point *b.* in 1.16. regarding the appropriate agency for enabling fusion.

2.7. Computer Simulation Short Critique

Summing up, it is apparent from the above that a central concern when blending materials digitally is the setting out of the simulation. Affecting this set-out are the in-built capabilities that design simulation software has of incorporating agency that can only occur computationally and is disconnected from physical reality.

2.8. Proposed Methodology- Design Concerns

A first design concern is to therefore discern the solely virtual from the virtual-but-physically-derived capabilities. The method proposed for this discernment is to research on *industrial FGM manufacturing techniques* and/or to work out *applied loads* in order to make the simple claim that the forces utilised/applied physically can also be attributed in the computer. A second concern is that these manufacturing techniques ought to be divided into *contact* and *non-invasive*. Once the appropriate agency characteristics are identified, the third concern is whether they can be input in the computer in a *measured* manner, or they need to be *approximated*. Regarding the latter, an issue arises when the characteristics of an FGM output from a simulation with approximated inputs, differ from the physical version of this FGM. This can typically occur as particle-based design simulations can only simulate a limited range of scales (Winsberg, 2014), as opposed to multi-scale parallel simulations that can accurately reproduce the quantum, micro, as well as visible scales[8]. In this case a quantitative versus qualitative objective can make a difference as:

> "If we are using a simulation to make detailed quantitative predictions about the future behaviour of a target system, the epistemology of such inferences might require more stringent standards than those that are involved when the inferences being made are about the general, qualitative behaviour of a whole class of systems."
> (Winsberg, 2015)

But also, according to Winsberg (2015) "it is unlikely that there are very many real examples of computer simulations that meet their strict standards. Simulation is almost always a far more idealizing and approximating enterprise". As it has already been argued, however, meeting these standards is a constant (albeit unrealistic) endeavour, while at the same time one is conscious of the unavoidable resort to approximation.

2.9. Curtain Wall Interface Design- Task Definition

Moving into the main design focus of the research, the following analyses the workflow of redesigning (through a multi-material) the interface of glass to its adjacent aluminium frame in a curtain wall panel.

2.9.1. Curtain Wall Interface Design- Simulation Parameters

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[8] Particle-based simulation software was chosen in this case due to its wide availability to designers and architects, as opposed to multi-scale simulations that are only used in science.

Following up on the previous design studies, the two main parameters discussed more extensively are, *a.* the formal characteristics of the mould within which materials will be ‘poured’ digitally and fusion simulated, and *b.* the material sub-sets that will form this multi-material entity. In addition, the agency that is attributed in the simulation is also briefly touched upon.

2.9.2. Sub-Material Selection

In terms of the selection of materials, the objective of the design experimentation was to tap into research that is taking place in fields adjacent to architecture, therefore basing the creation of any multi-materials on verified practices. In this regard, initial research showed that there are no present-day cases in which glass has been made to fuse with aluminium in an FGM directly. Further investigation, however, indicated that it is possible to fuse together aluminium with alumina (Birman and Byrd, 2007), namely in “aluminum matrix composites reinforced by nanoceramic particles [that] are widely used in military, airplane and automotive industries because of their high strength, modulus, wear resistance and low thermal expansion coefficient” (Mahboob, Sajjadi and Zebarjad, 2008, p.240). In addition, there currently exists “a method of percolating […] molten $CaO\text{-}ZrO_2\text{-}SiO_2$ glass into […] [a] polycrystalline sintered alumina substrate to prepare glass-alumina functionally graded materials” (Yu, et al., 2007, p.134). With this in mind, it would be technically feasible to use alumina as an interface material subset in an aluminium-alumina-glass multi-material entity. Effectively, this partially resolves the problem regarding the large number of materials used in a typical curtain wall glazing. The aluminium, silicone, polyetherimide, EPDM rubber, insulating glass and myriad other materials that are employed in generating these parts and are then discarded, can be replaced here by a mere three materials. These can be simply fabricated in a multi-material employing centrifugal casting (or ideally 3D printing when this becomes feasible), effectively doing away with the multitude of convoluted and hazardous processes typically involved in the generation of a curtain wall panel.

Going back to the simulation itself, indicatively, in its liquid state, glass has an approximate density of 2,500 kg/m^3 and dynamic viscosity of 100 Pa·s (RealFlow 2014 Documentation, 2014), alumina a density of 2,830 kg/m^3 and dynamic viscosity of 0.0054 Pa·s, while for aluminium the same values as previously were input in the simulation.

2.9.3. Simulation Mould- Initial Design

Continuing with the mould, this was initially designed as a continuous enclosed volume and with the same proportions and dimensions as the ones of a standard curtain wall segment consisting of a double-glazing pane affixed to an aluminium frame. The main design concern, here, was in terms of the appropriate formal characteristics that would allow for a more effective transfer of loads between glazing and structural frame. It was hence deemed necessary to firstly investigate examples where graded connections achieve this load transfer in a successful manner.

2.9.4. Enthesis

More specifically, places like the enthesis, which is the point where the soft tissue of the muscular system attaches itself to the osseous tissue of the skeletal system in the human body, utilize a range of ingenuous “mechanisms for overcoming the mechanical mismatch” (Thomopoulos, 2011, p.273) between the two materials. This mismatch is due to the inherently different material and structural characteristics of these two types of tissue, with bone having “a modulus on the order of 20 GPa and tendon […] [having] an axial modulus on the order of 450 MPa and a transverse modulus on the order of 45 MPa” (Thomopoulos, Birman and Genin, 2013, p.12). As a result, there are very high stresses developed in the place where they connect. For that stress to dissipate, an abrupt connection fastening the two together is eschewed for a type of graded material that incrementally changes its properties from osseous to fibrous.

2.9.4.1. Enthesis- Macro-Scale Mechanisms

The main aim therefore for configuring the materials at their point of fusion was to borrow from this naturally occurring example in order to inform the design of the blending container. At the level of the organ, one of the main techniques are the multiple attachment sites that eliminate any isolated connections between muscle and bone. Furthermore, another mechanism employed in the connection on a tissue level, is “the complex interdigitation of the layer of calcified fibrocartilage with the adjacent bone that secures attachment” (Benjamin, et al., 2006, p.479). Lastly, on a formal level again, “the degree of the stress singularity […] depends on the angle of attachment; a shallow angle of attachment ameliorates [this…] singularity” (Thomopoulos, 2011, p.273).

Effectively, the macro-scale formal mechanisms can be summed up as *a.* multiple rather than just a single attachment site, *b.* a shallow angle of these attachments, and *c.* interdigitation. Based on the characteristics of existing cladding panels, the mould splits from a single (aluminium core) into two vertical volumes that correspond to the two panes of the double glazing in the panel. The outer of these two panes is completely solid in order to form a seal from the external environment, while the inner one needs to have a series of openings for air to circulate within the glazing cavity. The enthesis principles were therefore introduced at that point and rather than having a singular point of linkage at the area where the aluminium frame links with the glass, the connection was split into multiple points that were all inserted into the receiving volume at a shallow angle (Figure 04). This effectively accommodated both the need for openings, as well as the stability and effective bonding between the two materials, together with the capacity to have minute amounts of flexibility (to facilitate thermal expansion) that a completely solid connection would not offer.

2.9.5. Simulation Mould- Design Development

Here, it also needs to be stated that there is a vast amount of analyses concerning the structural function and behaviour of the enthesis, with small parts of this body of work selectively filtered out to inform the design operation presented. Whether the sophisticated reciprocity between material and form found in the enthesis would function equally well here[9], is something that would require a different focus and is not in the scope of this research to attempt to tackle in the structure to glazing interface. This is also since the design research presented is by no means a strict protocol to adhere to when designing multi-materially, but rather a methodological framework that can be openly adjusted to a high degree of scientific specification, or on the contrary remain within the domain of a purely design-oriented pursuit[10].

2.9.6. Agency Attribution

In terms of the third parameter, namely the agency used in the blending simulation, the main objective in this instance was to again base this on existing FGM manufacturing techniques, as well as on the structural analysis of a standard double-glazed unitized panel.

2.9.7. Structural Analysis

Concerning the analysis, this was performed in collaboration with AKT II Envelopes Ltd., using the finite element software SJ MEPLA for the glass, SOFiSTIK for the connecting bracket and SAP 2000 for the aluminium frame[11]. According to senior facade engineer Iain Bleakley (2016), the results show that the maximum stress and displacement occur in the middle of the outer glass pane of a double-glazed unit (Figure 03), “although there are [also] some less high stress concentrations at corners and edges on other faces.” Looking into the colour diagrams of these analyses, the loading patterns are of a radial nature, with the centre and corners of the panel being the areas affected the most. Additionally, “for the stresses in the framing members the highest [ones] will occur where the frames are fixed (assumed to be at the corners which is usually the case) […] Adding more material according to the stress patterns is a way of making material efficient.” Summing these up, there are *a.*

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[9] Bearing in mind that the formal attributes of the enthesis were preserved, but the original fibrous and osseous materials were replaced by aluminium, alumina, and glass.

[10] In fact, apart from the enthesis principle that was used in this case, another technique for generating the connections and removing part of the otherwise solid material between the aluminium frame and the glass, would be a topology optimisation routine. This was employed by Tomlin and Meyer (2011) and Galjaard, et al. (2015) in the redesign of metallic structural elements and involves the use of the optimisation software to initially work out the loads acting on a given element and iteratively remove material where it is not structurally needed.

[11] The fact that the most straight forward way for the analyses to be performed was on discrete, homogeneous material parts, comes to demonstrate even further the current limitations of engineering analysis software in integrating graded material information.

high stresses and displacement occurring at the middle and corners of the unit and, *b.* high stresses where the aluminium frame is fixed to the slab supporting the panel.

2.9.8. FGM Manufacturing Techniques

Regarding the existing FGM manufacturing techniques, the main ones include centrifugal powder forming and gravity sedimentation among others. As far as the mould configuration is concerned, there were several sub compartments[12] placed vertically within the master mould that contained the materials to be fused over the course of the simulation. As the aim was for these to be mixed crosswise across the vertical mould, a centrifugal force was deemed appropriate to achieve this.

2.9.9. Curtain Wall Interface Design Output

Consequently, with all the above parameters in place, the simulation was initiated with the alumina placed in the central part of each side and aluminium and molten glass on either ends of the container. The blending in this case reached the required formation[13] after approximately ten seconds and eventually terminated at twelve (Figure 05).

2.9.10. Curtain Wall Interface- Evaluation & Critique

Due to the centrifugal force affecting the distribution of material, the gradient that was formed between the aluminium, alumina, and glass was of a circular nature and very similar to the one generated in the load analysis. Although this is a detail of the overall panel, one could envisage how the application and attuning of the centrifugal force with the loading pattern could distribute the aluminium where it would be needed for further structural support, corresponding in this case sub-material distribution within the larger multi-material to the loading dissipation on the panel.

Effectively, in terms of the aforementioned point *a.*, the high stress and displacement at the corners of the panel was corresponded to by the radial aluminium distribution, while the ones occurring at the middle of the panel could be dealt with by the “thickness being varied in the glass. [The glazing could be] technically ‘oversized’ in some areas to allow for the maximum stresses in the overall pane, [which] could allow for more efficient use of the material. The downsides of doing this with glass is that it may cause […] some pretty ‘wacky’ visual distortions and of course [there would be the need for] finding a way to mass produce cost effectively” (Bleakley, 2016). Regarding point *b.*, the high stress developing on the aluminium frame was dealt with by making the mould form more voluminous at that location, therefore allowing for a larger amount of aluminium to be placed within the corresponding material sub compartment. Effectively, this higher concentration of material would reinforce the frame locally and minimize any possible deflections.

2.9.11. Adequate Blending Characteristics- Main Criteria

Regarding the visual evaluation of the sub-materiality inter-dispersal, the micro-characteristics of a graded structure are described in extensive detail by Miyamoto et al. (1999, p.41):

> “First, the volume fraction of b increases with increasing distance from [top] to [bottom]. The size of the b particles also increases in the same direction. In addition, the b particles become more angular, and there is more contact between them as the volume fraction of b increases. At the far [top], the microstructure consists of isolated b particles distributed uniformly throughout a matrix of a, whereas at the far [bottom] the b phase forms an interconnected network with islands of a existing along grain boundaries of b. The porosity present within this structure is located only within certain localized regions in the structure. For those parts of the material that contain nearly equal amounts of a and b, the porosity is

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[12] Six in total; two for aluminium, two for alumina and two for glass (the order that these are placed in is also an important parameter, especially when visualising and fabricating the multi-material).

[13] This criterion determining the interspersed patterning of the neighbouring materials in the fused regions is visually verified and explicitly presented in 2.10.11.

> located entirely within the a phase. At high contents of b, the size of the porosity is smaller and located entirely within the b phase.” (Figure 06)

This effectively forms a specific piece of criteria against which to assess the FGM formation during the simulation and determine whether to terminate it, or not. If for instance, the size of one of the mould sub-compartments was too wide, the material contained within would ‘dominate’ the adjacent ones and effectively form a matrix within which the other substances would be diluted, forming an alloy-like material. Additionally, in the case where a temperature fall-off parameter was incorporated[14], the substances would coagulate too quickly, reaching a solid state before fusing.

Aside from this, the position of the sub-compartments in the interior of the containing vessel was also important. Materials of two sub-compartments neighbouring vertically would fuse better as gravity would pull one substance downwards into the other. Additionally, a thinner vessel section at the border between two sub-compartments would mean that there would be less material to be fused and possibly not enough for an extensive gradient to be formed. In all these cases (Figure 06), the main criterion for evaluating the resulting multi-material arrangement would be the creation of adequate gradients as specified above. Getting the right balance to attain this would necessitate a synergy between all the parameters mentioned.

3.1. Visualising Fusion

3.1.1. Problem Definition

Moving forward, a main problem encountered in the visualisation end of the design workflow was the fact that there are limitations on the type of materials that can be rendered on a graded material mesh[15]. Colours and materials of solid parts can be easily mapped and attributed on the output mesh using per-vertex data, however, when it comes to transparent segments, commercial rendering engines cannot attribute these in continuous volumes that consist of more than one material. The following will demonstrate a workaround to this issue by utilising alpha channels in a raster graphics-editing program in order to remove a default solid material temporarily used in place of one that should be transparent, and the eventual substitution of that by glass.

3.1.2. Visualisation Workflow

Looking into the custom workflow, the first point that one ought to mention is that the six particle systems[16] were stored in the simulation software sequentially. When importing the particle mesh generated in the simulation program (RealFlow) to a visualisation software (Autodesk Maya 2017) there is a way to link each mesh vertex to the corresponding particle systems that had an influence on it and to achieve that way accurate colouration. In terms of visualising these colours, a multi-material shader[17] (Realflow Melt Shader) was assigned to the overall mesh and fluid sub-material placeholders (six in total in this case) were created within the multi-material shader. Each one of these was corresponding to the six original particle systems that in their turn correlated to six b-rep segments on the mesh. Sub-material assignment, started off from particle system 01 to mesh segment 01 (middle right aluminium), then particle system 02 to mesh segment 02 (right alumina), particle system 03 to mesh segment 03 (right glass), and then continued with particle system 04 to mesh segment 04 (middle left aluminium), particle system 05 to mesh segment 05 (left alumina), and particle system 06 to mesh segment 06 (left glass) (Figure 07).

3.1.3. Simulation Critique- Non-Variability of the Gradient Extents According to Different Sub-Material Properties

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[14] i.e. the temperature of the digital molten materials was reduced gradually, so that they solidify as would happen in physical reality.

[15] The simulation software employs a mesh to generate “a three-dimensional representation of the outmost particles” of the blending simulation. “[In essence,] the mesh engine puts a sort of skin over these particles to visualize the fluid’s volume” (RealFlow 2015 Documentation, 2015).

[16] As per Figure 04, two for aluminium, two for alumina and two for glass.

[17] A melt shader is essentially a rendering multi-material that consists of base sub-materials.

Once this attribution was made, an inbuilt algorithm generated the gradient distributions in-between the various sub-material segments. As a side note, the standardized nature of this algorithm meant that the physically occurring principle of material properties affecting the size and extent of grading within a multi-material was not incorporated into the program, which is something that results in a fixed type of gradient formation.

3.1.4. Visualisation Workflow Continued

Going back to the visualisation process, as already mentioned, the glass material corresponding to particle systems 03 and 06 could not be transparent as rendering software does not have this capability. One must therefore render these as solid sub-materials acting as placeholders that will be substituted eventually. A subsequent problem, however, was that because the sub-materials were sequentially assigned and numbered one could not just remove particle system 03 (right glass) and particle system 06 (left glass) segments in order to add an image of a glass sub-material below them.

The first step of the workaround to this was to generate an initial render of particle system 01, and particle system 02 (+alpha channel), leaving all other sub-material holders empty (Figure 08). The resulting render was of the multi-material part but only depicting two out of six sub-materials, the other four being empty and therefore being the same as the background of the scene. The file was saved (render 01) and the next step was to generate a second render of particle systems 01, 02, 03, 04, and 05 (+alpha channel) (Figure 08). This means that rendered in the final scene were five out of a total of six sub-materials, the glass sub-material of particle system 06 left empty and a default solid sub-material used for the glass-sub-material-to-be of particle system 03 (Figure 08).

All render files were imported in Adobe Photoshop, the alpha channel of render 01 was imported into render 02, and the channel was then selected and inverted in order to only select the empty material-less background space together with the default sub-material substituting the glass material of particle system 03. Once selected, these were all removed from the image file. Correspondingly, the alpha channel of render 02 was selected, inverted and removed from the file. What one was left with were the following sub-materials: particle system 01 (middle right aluminium), particle system 02 (right alumina), particle system 03 (void), particle system 04 (middle left aluminium), particle system 05 (left alumina), and particle system 06 (void).

Render 03 (fully glazed part) was then simply imported into the file, placed under render 02 and glass takes the place of the two voids (Figure 09).

3.1.5. Visualisation Critique and Evaluation

Regarding the shortcomings of the output of the described procedure, on a closer analysis it can be argued that the ‘final image’ of the part was not quite an accurate representation of a partly transparent multi-material. More specifically, there were internal reflections that were clearly visible in the rendering of the fully glazed surrogate part (render 03) (Figure 07) that would only occur on a single material. An accurate representation would of course be one where the glass segments picked up reflections from their neighbouring sub-materials both on a surface, as well as deeper, interior level. On this construal, one could ask what an acceptable degree of closeness to reality of the final render would be. An answer to this would be that the overarching aim is for the rendered representation of a multi-material to appear as real as reality itself (as discussed in 2.8.). A further point would then be that attaining this level of fidelity is potentially not feasible, with a subsequent response being that one ought to nevertheless keep striving to achieve as close a resemblance as technically and perceptually possible.

3.2. Materialising Fusion

3.2.1. Materialisation Objective

On the output end of the whole process, the following will explore the feasibility of converting the digitally generated multi-material into one that is physical. Earlier parts of this research were first published in the International Journal of Rapid Manufacturing (7(2/3), pp.277-294), with the part that follows being a reframing of this initial investigation. As previously discussed, alumina can co-exist together with glass in a multi-material, as well as with aluminium in another. These FGM, however, are mainly manufactured in very small scales using specialised equipment in material research laboratories. In effect, due to the inaccessibility of these facilities and the scientific knowledge required to make use of this equipment, the method followed here was to utilise commercially available fabrication technologies in order to manufacture the simulated FGM.

3.2.2. Digital to Physical Gradient Conversion- Problem Definition

When attempting to do this the main problem was that although the colours that represented graded materiality were visible in the simulation environment, exporting these to a file format for 3D-printing was not feasible. This was as exporting the mesh in the file formats available within the software resulted in the material/colour values being lost. In effect, in order to attain point *f.* in 1.4. (of linking directly design simulation and fabrication) the colour values had to be translated into numbers that could be written in a text file, exported from the simulation software and reapplied on the mesh in a commercial 3D modelling software. A 3D printable file format could then be exported from the modelling platform for fabricating the part in a multi-material.

3.2.3. Digital to Physical Gradient Conversion- Computational Workflow

3.2.3.1. Fluid Weight Data Colouration

The first take on converting this data was to use the per-vertex weight of each particle emitter that can be extracted as a decimal number. This value is an average of the influence that each particle emitter has on the colouring of each of the vertices of the mesh. The Python script devised to export the per-vertex weights was the following:

```
for i in range (0, total number of mesh vertices):
        vertexWeight= ParticleMesh.getFluidsWeightAtVertex(i)
          file.write (str(vertexWeight))
```

Running the script initially resulted in the weight data being output in this format: [(‘01_Aluminium_Fill_Object’, 0.0), (‘02_Alumina_Fill_Object’, 0.0), (‘03_Glass_Fill_Object’, 0.0), (‘04_Aluminium_Fill_Object’, 0.0), (‘05_Alumina_Fill_Object’, 0.0), (*‘06_Glass_Fill_Object’, 1.0*)], which in this case indicated that particle emitter 06 would have a 100% influence[18] on the colouration of that particular vertex.

At another index of the data list, the output corresponding to a different vertex would be: [(‘01_Aluminium_Fill_Object’, 0.0), (‘02_Alumina_Fill_Object’, 0.0), (‘03_Glass_Fill_Object’, 0.0), (*‘04_Aluminium_Fill_Object’, 0.27106717228889*), (*‘05_Alumina_Fill_Object’,0.20003880560398*), (*‘06_Glass_Fill_Object’, 0.52889406681060*)], indicating that there are three particle emitters affecting this mesh point, with the respective numbers representing different degrees of influence and the addition of them being 1.0.

When all values were then saved in a .doc file, an initial issue was the very large file size that for 297,561 vertices in total came to an overall word count of 3,411,613 words over 17,576 pages equating to 68.1 MB. A file of this size would make file handling times very slow and require high processing power to retrieve the data. When the text preceding each of the numerical values (in the form of ‘x_x_Fill_Object’) was removed, the file size was reduced to 14.2 MB, 1,785,906 words and 6,581 pages. Being easier to handle, this file was used subsequently for recolouring the mesh.

At this stage it was anticipated that the correspondence between each mesh vertex and the fluid data values would in principle enable a direct colouration of the imported mesh. When converting the data into RGB values and painting these on the mesh, however, the result was an accurate distribution of gradients, but an incorrect colouration. This was due to the fact that the weight data was a representation of the influence that each emitter colour had in the pigmentation of a vertex rather than a direct colour value. This colouring would be straight forward in the case of a 0.0, 0.0, 0.0, 0.0, 0.0, 1.0 value, as particle system 06 would be the only influence on vertex pigmentation, with an RGB

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[18] 1.0 being equal to 100%.

value of (178, 216, 239). The problem would be when particle systems 04, 05 and 06, each with a different RGB colour of (87, 87, 87), (133, 13, 83) and (178, 216, 239) respectively, would correspond to the aforementioned 0.0, 0.0, 0.0, 0.27106717228889465, 0.20003880560398102, 0.52889406681060791 output.

Initially, the attempted workaround was to convert the RGB values to integer numbers and multiply these by the weight data values. For example, RGB (87,87,87) would be converted to 5723991 and then 5723991*0.27106717228889465≈ 154547757. This operation was then performed for the other particle systems expecting that the addition of the resulting numbers would in principle result in the right colour. When considering, however, that an RGB integer stems from this formula: RGB Integer= Red + (Green*256) + (Blue*256*256), this workaround was not possible. The correct approach should have been to multiply each RGB with the fluid data value: 87*0.27106717228889465= 23.58284398913383 and place the result in the RGB integer formula to obtain a single integer: RGB value= 23.58284398913383 + (23.58284398913383*256) + (23.58284398913383*256*256). A subsequent hurdle, however, would be in averaging out the integer numbers of the remaining particle systems in order to obtain a final, single RGB value.

3.2.3.2. RGB Colouration

In response to this, and in order to avoid the multitude of conversions that would have to occur in the above workflow, a Python script was developed in collaboration with Alex Ribao of Next Limit Technologies, the software company that developed the simulation software. Direct RGB colours were output in effect, with the text file indices consisting of 3 individual values for Red, Green, and Blue, and the file size being a manageable 10.3 MB. The following formula was then used to convert the colours from arithmetic to 8-bit per channel values: RGB (Vertex R Value (0 to 1) * 255, Vertex G Value (0 to 1) * 255, Vertex B Value (0 to 1) * 255) (Figure 10).

A last issue that then occurred was the non-correspondence of the number of RGB values in the text list to the total number of mesh vertices, which is something that led to incorrect colouration. When for instance the mesh was exported from RealFlow in the .obj file format and imported in Rhino, the number of vertices were up to 15 less than the ones of the original mesh. Consultation with Next Limit Technologies indicated that there was no solution to this problem. The eventual workaround was to export the mesh in every available file format, counting the number or exported vertices every time and concluding in the end that .lwo was the format that preserved the total vertex count in both platforms.

The accuracy of this data conversion workflow was tested through a multi-colour sandstone 3D-print that was coloured according to the RGB value list. The resulting artefact exhibited identical colours and gradients to the digital model, however, the objective here was to attain direct multi-material correspondence as opposed to the representational attributes of the sandstone print.

3.2.4. Physical Gradient Fabrication

When aiming to convert the computer-generated gradients into ones that are physical, the main issue is that direct fabrication of gradients is not yet possible. In order to 3D-print multi-materially one must convert any gradients into discreet sub-materials, which when combined give the impression of a gradual transition. This meant that the continuous colouration of the mesh resulting from the above workflow had to be converted into a step-wise sub-material distribution. In effect, this would leave some of the attributes of the part intact while affecting others.

3.2.4.1. Stepwise Distribution

The parameter that would get affected by the conversion of the continuous to the step-wise would be the structural behaviour of the multi-material. This was expected to change due to the additional forces developed at the boundaries of the sub-material segments. At the same time, further research and loading tests would need to be conducted in order to identify the specific structural differences between a glass-alumina-aluminium and Polyjet plastic FGM. Regarding the unaffected attributes, it would be possible to preserve in the fabricated part the same incremental optical qualities occurring in the transition from glass to alumina to aluminium in the digital model, maintaining in effect the gradual transition from opacity to transparency. As it will be shown the finer the discretisation, the larger the visual impression of a gradient in the discretised mesh.

3.2.4.2. Gradient Discretisation Workflow

Consequently, the conversion of a continuous to a step-wise multi-material was achieved by using a Visual Basic script in Rhino 3D, which was applied on the gradually coloured mesh, isolating the mesh faces of a similar colour family. As aforementioned, in commercial 3D modelling software mesh colouring occurs on vertices as opposed to faces. The RGB colour of each of the vertices that make up a face was therefore retrieved through the script and stored in an array together with the corresponding face. The indexed per-face vertex values were then compared to a user-input RGB value range and if their average was within that range, the face was extracted from the larger mesh topology and stored in a new array. Running this routine recursively with a different RGB range every time resulted in the grouping of all faces in similar colour families (Figure 11).

3.2.4.3. Gradient Discretisation Limitations

In addition, the relative size of each of the sub-material segments depended on two main parameters. Firstly, the resolution of the mesh i.e. the size of its constituent faces, and secondly the highest and lowest values of the user-input colour range. A high-resolution mesh made up of a large number of smaller faces, and a smaller difference between the maximum and minimum values of the colour domain would result in the mesh being cut down into very fine segments that would give a more convincing visual impression of gradation. At the same time, this would result in a larger number of sub-material boundaries within the multi-material that would have an impact *a.* on structural behaviour and *b.* on the neighbouring Polyjet sub-materials in the multi-material pre-set palettes not being sequentially enough to correspond to the number of sub-materials in the print. As the colour and optical gradation sequences of sub-materials in the printing palettes were always nine in total, the VB script was run for the equivalent number of times, resulting in nine colour groups of mesh face clusters that corresponded to the availability of sub-materials, limitations in mesh subdivision and the target colour range.

Looking back at the initial fluid weight data workflow outlined in 3.2.3.1., it became apparent that this routine would have sufficed for mesh discretisation and multi-material fabrication. This is because although the colours themselves were incorrect, the distribution of gradients on the mesh was accurate. In effect, the correct positioning of the incorrect colours on the mesh and the user inputting a different colour range (corresponding to the incorrect colours) would have been enough to discretise the mesh in a successful manner. This was also because the VB script above was working with median values.

Regarding the gradation resulting from the colour averaging routine and considering that the objective was to preserve the impression of gradients despite the necessary discretisation, the application of the above workflow led to a visual deviation from the gradients of the digital model. This was because the gradients in the original were originally formed between the glass and alumina (light blue and red) and alumina and aluminium (red and grey) regions. In effect, the discrepancy came from the averaging out of the mesh vertex values, which meant that when a face in the alumina and aluminium region had the same average RGB value as a face in the glass and alumina area, it was considered of the same colour family and the continuous mesh faces connecting the two were converted into a single discrete segment. However, a sub-material placed between the alumina and clear glass areas would not achieve the same gradient effect on the opposite end where alumina fused into aluminium.

A simple workaround to this issue was to divide the continuous mesh segment into smaller clusters and compare these to the gradients in the digital model. The clusters corresponding to the “pools” of alumina dispersed in its surrounding aluminium matrix were extracted and different sub-materials applied to them. Additionally, according to the pre-set Polyjet multi-material palettes the maximum number of base sub-materials that can be used in a print are three. The range of “material properties … from rigid to flexible and clear to opaque in a wide range of colours and hues” (PolyJet Multi-Material 3D Printing) should fall within these base materials, and as the main quality aimed for was a transition from opacity to transparency, the cyan-magenta-clear sub-material palette was used in the end[19].

As six out of seven sequential sub-materials between the VeroClear and VeroMagenta base materials were already assigned at the glass and alumina fusion region, there had to be a different set of sub-materials applied to the opposite region where alumina fused into aluminium. Following the manual discretisation, there were four sub-material segments formed between these two base materials (represented here by VeroMagenta (alumina) and VeroCyan (aluminium)) and seven available sub-materials between these two in the Polyjet palette. The correspondence of the four segments to each Polyjet sub-material was again made with the preservation of gradation in mind.

Once all sub-materials were attributed in the two regions accordingly, the result was an incremental progression from VeroClear (glass) to VeroMagenta (alumina) to VeroCyan (aluminium).

3.2.4.4. Mesh Thickening Limitations

A last issue that was encountered once the mesh was discretised and all sub-materials applied to each part was that the non-volumetric mesh shells had to acquire thickness for multi-material printing. They were therefore offset to the minimum acceptable depth of 0.4mm. As the edge vertices of each part had normal orientations that overlapped with the vertex normals of their neighbouring strips, however, the adjacent extrusions intersected, which in turn meant that most of the sub-materials cancelled each other out and in the end only the three base materials were printed (Figure 12).

A solution to this was devised in collaboration with Marios Tsiliakos (from Digital [Sub]stance and the University of Innsbruck), who generated a Grasshopper 3D definition for aligning the edge vertex normals of each piece. According to Tsiliakos, the workflow consisted of the following steps:

1. The discrete parts were joined back into a single mesh, all vertices welded, the mesh was ‘cleaned’ to attain a comprehensive topology, and the colouration of the initial sub-material parts was applied to the joined mesh.
2. All mesh normals were unified by average approximation of neighbouring vertices and the mesh was offset to the above mentioned 0.4mm.
3. The corresponding colours were applied to the offset mesh using a face-by-majority-rule between the corresponding vertices of both the original and offset meshes.
4. Any remaining naked edges were extracted and grouped in pairs and quad mesh faces were created in-between these edges to generate the mesh perimeters.
5. All original discrete, offset and perimeter meshes were joined into watertight mesh clusters.
6. The clusters were assessed for colour inconsistencies (if any were present, the prevailing colour would be applied to the whole cluster), grouped by colour, and each one assigned to a new layer with the colours applied as meta-data ready for 3D printing.

Initial testing showed that a workable multi-material print can result from this mesh segment thickening method. While there still needs to be a substantial amount of manual correction of the remaining self-intersecting regions, the forthcoming final step will be to fabricate the segment and perform a visual inspection identifying any divergence from the digital model.

3.2.5. Conclusion and Discussion

Direct multi-material fabrication is a process that is still in its nascent stage and as it has been presented, a degree of mediation is still the case. Fused materials had to be translated into gradient colours that were then converted into numbers, which were converted back into gradient colours, discretised into singular colour groups and output as materials, which, however, had different properties to the ones originally computed. It is a matter of time until direct multi-material integration, but until then it is to be hoped that fabrication research as the one presented will form a contributing step towards it.

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[19] Of the four colour-transparency rigid PolyJet palettes available.

In fact, currently “there is nothing out there that can do true multi-material manufacturing” (Zolfagharifard, 2013). It is, however, envisaged that “real innovations will happen in the research world. Multi-material is the next evolution in the technology… you’re probably looking at a 5- to 10-year timescale to see real multi-material integration” (ibid., 2013).

Anticipating this imminent reality, a novel computational design workflow was presented, of simulating the fusion of materials using particle systems, in a design approach where form does not take precedence over materiality, and where material behaviour is a ‘peer’ in the co-evolution of designed form, agency, as well as materially emergent formal and fusional attributes.

The principle contribution to knowledge was the formulation of a set of prerequisites for the validity of material simulation use in architectural design, plus the creation of a visualisation workflow for the (relatively) accurate representation of a multi-material that is partly transparent, and the linking of simulation to additive manufacturing through bespoke Python and Visual Basic coding. Representation can now be made simply with standard 2D graphics and 3D modelling software, while the incompatibility between CFD and 3D-printing is resolved by converting gradient material data into colour values for (partially accurate) multi-material fabrication.

As developments in the relevant manufacturing techniques are rapidly advancing towards the aforementioned integration, this research lays out a work path for the architect and/or architectural designer of this forecast, imminent future, who will be called upon to operate within a changing landscape, from a logic of discreteness to one of continuousness.

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Image Captions

- Figure 01: Stainless Steel- Zirconia Functionally Graded Material Sample. Zirconia of 100% consistency (left) is gradually merging into 100% steel (right) continuously within one volume. Scale bars from top to bottom are x100, x200, and x500. Reprinted from Materials Letters, 37/6, Jeong-Gu Yeo, Yeon-Gil Jung, Sung-Churl Choi, Design and microstructure of ZrO_2/SUS316 functionally graded materials by tape casting, 307 & 310, Copyright (1998), with permission from Elsevier.
- Figure 02: Front and Side Views of Copper Aluminium Blending Simulation, taken at 79 Seconds. The openings cover approximately a quarter of the total surface area of the panel.
- Figure 03: Stress Analysis of a Curtain Wall Glazing Unit, showing stress distribution on the glass (left) and on the frame (right).
- Figure 04: The Various Stages of the Blending Simulation. Shown from top to bottom are the mould (indicating the sub-compartments for aluminium, glass, and alumina), the liquid materials at the first second of the simulation in the middle, and the final blending distribution at the twelfth second at the bottom. The orange circles indicate the circular arrangement of the aluminium and alumina that match the loading pattern.
- Figure 05: Exterior View of the Multi-Material Mullion Interface, showing its relation to the original curtain wall glazing segment.
- Figure 06: Top Left: “Diagram of a Hypothetical Graded Structure, that has gradients in several different microstructural features” (Myiamoto et al., 1999, p.42); Top Right: The Graded Structure Achieved in the Blending Simulations that has the same characteristics as the diagram by Myiamoto et al. (1999),

Bottom Left: Case 01- Uniform Dispersal of Substance A into B, exhibiting an alloy-like material distribution; Bottom Middle: Case 02- Non Dispersal of Substance A into B. The two materials have coagulated before a graded material structure was achieved; Bottom Right: Case 03- Limited Dispersal of Substance A into B. This is due to the thin vessel section resulting in limited material flow of A into B.

- Figure 07: Diagram of the material-less b-rep mesh showing particle system to sub-material to mesh segment correspondence.
- Figure 08: Renders 01, 02, and 03 (from top to bottom).
- Figure 09: The Final Render sequence.
- Figure 10: Diagram of the RGB Data Colour Conversion Routine.
- Figure 11: Exploded View of the discretised mesh layers.
- Figure 12: Close up Interior View of the Fabricated Multi-Material Mullion Interface. The nine initial sub-materials became four, due to offset mesh material overrides.