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COMPUTATIONAL AND CONCEPTUAL BLENDS:

The Epistemology of Designing with Functionally Graded Materials

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A thesis submitted in partial fulfillment
of the requirements of the Royal College of Art
for the degree of Doctor of Philosophy

London, May 2017

Copyright Statement

Abstract

Operating within the landscape of new materialism and considering recent advances in the field of additive manufacturing, the thesis is proposing a novel method of designing with a new type of material that is known as functionally graded.

Two of the additive manufacturing advances that are considered of radical importance and at the same time are central to the research have to do with the progressively increasing scales of the output of 3D printing, as well as with the expanding palette of materials that can now be utilised in the process.

Regarding the latter, there are already various industrial research initiatives underway that explore ways that various materials can be combined in order to allow for the additive manufacturing of multi-material (otherwise known as functionally graded material) parts or whole volumes that are continuously fused together.

In light of this and pre-empting this architectural-level integration and fusing of materials within one volume, the research initially outlines the anticipated impacts of the new way of building that this technology heralds. Of a total of six main anticipated changes, it then focuses on the impact that functionally graded materiality will have on how design is practiced.

In this attempt to deal with the uncertainty of a material realm that is unruly and wilful, an initial criticism posed of the *scant* existing methods for designing with multi-materials in the computer is that they do not consider the intrinsic behaviour of materials and their natural propensity to structure themselves in space. Additionally, these models essentially follow a similarly arbitrary assignment of sub-materiality within larger multi-materials, to the *hylomorphic* imposition of form on matter.

What is effectively proposed as a counter design technique is to computationally 'predict' the way materials will fuse and self-structure, with this self-arrangement being partially instigated by their physical properties. Correspondingly, this approach instigates two main objectives that will be pursued in the thesis:

- The first goal, is to formulate an appropriate epistemology (also known as the epistemology of computer simulations-EOCS), which is directly linked to the use of computer simulations to design with (*computational blending*). This is effectively the creation of a methodological framework for the way to set out, run, and evaluate the results of the simulations.
- The second goal, concerns the *new design methodology* proposed, in which the conventional material-less computer aided design methods are replaced by a process of constructing *b-rep* moulds and allowing digital materials to fuse with one another within these virtual frameworks. Drawing from a specific strand of materialist and cognitive theory (*conceptual blending*), the theoretical objective in effect is to demonstrate that form and material are not separate at any instance of the proposed process.

The resulting original contribution of the design research is a process model that is created in an existing simulation software that can be used in a standard laptop computer in order to design with functionally graded materials. The various 'stages' of this model are mapped as a diagrammatic design workflow in the concluding end of the PhD, while its main parts are expanded upon extensively in corresponding chapters in the thesis.

List of Illustrations

Acknowledgements

This thesis would not have been possible without the supervision of Dr. Jon Goodbun and Dr. Lambros Malafouris, whose guidance, comments and suggestions have been seminal to the progression and eventual completion of the PhD. In addition, a special thank you to Professor Susannah Hagan whose incisive comments in progress reviews over the past years have been key to getting the PhD on track, and to Roberto Bottazzi for his supervision, patience and very helpful discussions that took place from the beginning up to midway through the past several years of thesis development.

Gratitude is due for Dr. Harriet Harris, Adrian Friend, Fernando Rihl, and Boris Cesnik from the Royal College of Art. Also for Professor Rees D. Rawlings and Dr. Zahra Sharif Khodaei from Imperial College for clarifying things regarding functionally graded materials from a scientific point of view, for Alex Ribao from Next Limit Technologies for his invaluable computational help on material data transferring, and for Adam Bloomfield and David Morris from Industrial Plastic Fabrications for their consistent perseverance when trying to resolve the various problems with fabrication, on the multi-material printing end of the whole process. Additionally, for Marios Tsiliakos from the University of Innsbruck for the help with part of the computational design workflow, and for Iain Bleakley from AKT II Envelopes for giving his time and generating very much needed structural calculations.

Special thanks go to the Secretarial Office and the Scholarship Team of the A.G. Leventis Foundation, for the annual grants over the past three years that have been an immense financial help that came at critical times of the PhD. These in many ways allowed the focus to remain constant. Also, to the Council of the Sir Richard Stapley Educational Trust for the one-off grant, and to the awarding body of the conference funds at the Royal College of Art.

Over the past years, the latter allowed the research to be disseminated across a number of conferences and symposia. Further gratitude is for the following people and institutions that allowed this to happen: the ESARQ School of Architecture at UIC Barcelona and the *2nd International Conference of Biodigital Architecture & Genetics* in Barcelona, ENHSA (European Network of Heads of Schools of Architecture) and EAAE (European Association for Architectural Education) and the conference *What's the Matter? Materiality and Materialism at the Age of Computation* at ETSAB, ETSAV and the Chamber of Architects in Barcelona. The University of Northumbria and the participants at eCAADe conference in Newcastle for voting for my research paper *Material Fusion: A Research into the Simulated Blending of Materials using Particle Systems* to be awarded the Ivan Petrovic prize (awarded annually for the best presentation by a researcher under 35 years old). The Centre for Information Technology and Architecture at the Royal Danish Academy of Fine Arts, School of Architecture, Design and Conservation and the *Design Modelling Symposium* in Copenhagen, and the University of Melbourne and the *21st International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA 2016)*.

Additionally, to the people that published or were key to further dissemination of parts of the research: Brett Steele, Director of the Architectural Association, who initially put forward the idea and eventually enabled the AA symposium on multi-materials. Jovis Verlag GmbH in Berlin for publishing *Mixed Matters: A Multi-Material Design Compendium* and to Didier Faustino for featuring the article *From Opacity to Transparency. It is a (Mixed) Matter of Time/ De l'Opacité à la Transparence, Matière à Réflexion et Question de Temps* in the Archicréé Magazine in France. Also to Dr. Emine Mine Thompson, editor of the International Journal of Architectural Computing, to Dr. Daniel Richards, Professor Nick Dunn, and Alvin Huang, editors of the Special Issue: Additive Manufacturing in Architecture of the International Journal of Rapid Manufacturing, and to Nigel Tonks from Arup for awarding the Arup Prize for Emerging Talent in Architecture-Special Mention at the Royal Academy Summer Exhibition 2016, to the thesis model titled *Fusion Superseding Tectonics: Multi-Material Building Envelope Detail*.

Lastly, to my parents Mari and Antonis Grigoriadis and to my partner Lizy Huyghe that is about to give birth to the third member of our family, around the same time as the submission of this thesis.

Author's Declaration

During the period of registered study in which this thesis was prepared the author has not been registered for any other academic award or qualification. The material included in this thesis has not been submitted wholly or in part for any academic award or qualification other than that for which it is now submitted.

Kostas Grigoriadis

May 2017

01

INTRODUCTION

The research that will be presented herein is an investigation into the use of functionally graded materials in architectural design. Drawing from recent shifts towards incorporating material information in CAD, it includes a research into the ways that material fusion can be achieved computationally, and a proposal for *a new methodology of designing with functionally graded materials* (applied in the design of a building envelope detail). These are followed by a theoretical discussion concerning the traditional separation of form and matter, and an analysis of the cognitive processes *during* and the re-engaging of materiality and form *through* the proposed design workflow.

In this regard, the focus of the research is not to produce a fully resolved technical or material science-based investigation into how a building element can be designed and built with a functionally graded material, nor a formal or aesthetic analysis of the designed artefact[01]. Any

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01 An argument that will be posed later in the thesis is that the design generated should not be conceived as a finished artefact at any stage of the workflow.

technical or material research in what follows is performed extensively enough to inform the design decisions taken and does not form the main area of investigation. Instead, the focus of the PhD is to fundamentally *rethink how architectural design is conducted and how thinking when designing with functionally graded materials is affected* in parallel and as a consequence. This is in order to demonstrate the intrinsic link of form to materiality. Lastly, in order to analyse this thought process, interdisciplinary references from cognitive theory and from the philosophy of mind are utilised without, however, shifting the focus from the core of the thesis, which is digital architectural design.

1.1. Field of Study & Critical Frameworks

Starting off an investigation into general material research advances, the ten *MIT Technology Review* (2015) Breakthrough Technologies for 2015 consisted of, among others, helium balloons that use the layered stratospheric winds to navigate the globe and beam high-speed Internet access to remote locations (Figure 01). Additionally, a cinematic-reality interface that projects light into human eyes, making it blend seamlessly with natural light and therefore populating one's vision with virtual imagery promised to make the virtual appear as real as reality itself. Research in both of these technologies partly involved a material problem (in the build-up of the balloons' polyethylene envelope and in manufacturing the grain-sized projector in the case of cinematic-reality) but more interestingly, five out of the other eight technologies were related to material innovations per se. With this kind of research nowadays ranging from the atomic

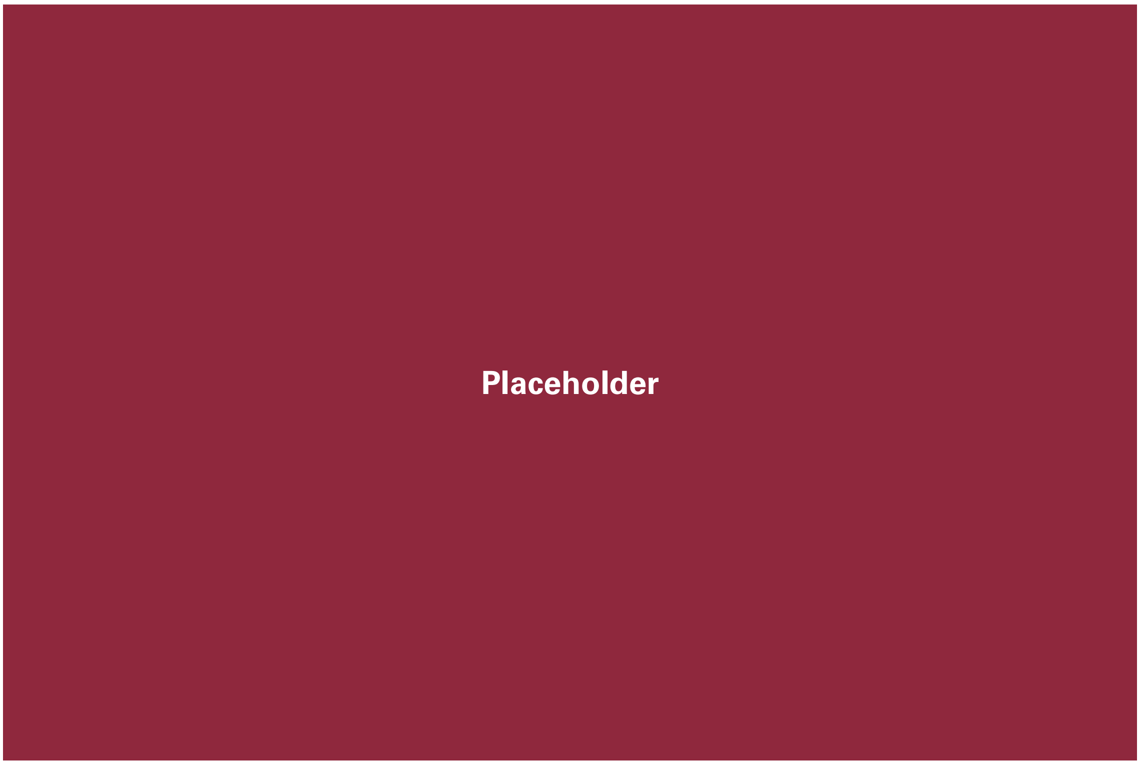

Figure 01: Project Loon by Google. The problem of combining inexpensiveness and durability during operation was resolved through the use of polyethylene and the introduction of safe handling practices during manufacturing of the balloons. This effectively increased the life of each balloon from eight to over one hundred days.

and Nano all the way to the visible scale it is possible to see the Nano-lattice architecture, liquid biopsy, brain organoids, supercharged photosynthesis and internet of DNA technologies (MIT Technology Review, 2015) as material level inventions. Additionally, taking this range of scales into account while looking through previous years of the review (MIT Technology Review, 2013, 2014), it is rather striking that there has been a steady decrease in the magnitude in which materiality has been intervened with. From the use of additive manufacturing for 3D printing jet parts in 2013, to micro-scale 3D printing in 2014, the natural continuation of this lineage was the creation of Nano-scale material lattices in 2015 (Figure 02).

What one can effectively extract from considering these reviews that capture the forefront of scientific and technological innovation, is that there are two main ongoing changes taking place currently. Firstly, in what material research and the definition of materials themselves actually are, and secondly in how matter interfaces and is affected by information and the digital domain. Or as Marcelo Spina (Spina and Gow, 2012, p.6) aptly suggested:

> "We live in an age of permanent mutation and continuous adaptation [...] Now, what if material itself was put into question? What if the very assumption of material as the purest, stable and discrete property upon which we formulate and construct often unstable things, would also become susceptible to change?"

Placeholder

Figure 02: The World's Smallest Glassy Carbon Nano-lattice, built at the Karlsruhe University of Technology using 3D laser lithography to generate the initial lattice arrangement. This was followed by pyrolysis in a furnace that shrank the lattice by 80%. The scale bar at the bottom right measures five micrometres across its length.

1.1.1. Contemporary Material Classification

Regarding this shifting definition of materiality, according to Adam Drazin (Drazin and Küchler, 2015, p.xxi) there has been a transition from materials that are reactive ("appearing in pre-determined and pre-intended uses in reaction to human action") to ones that "we can no longer depend on the predictability of" and which are active, *agentic* "and [...] much more causal in social and epistemological situations". This unpredictability can be said to go hand-in-hand with the aforementioned capability to alter matter all the way down to the atomic level, which is consequently initiating a Neo-Cambrian explosion of all sorts of stuff being concocted on a nearly daily basis. In this jungle of matter that is starting to exist out there (Carpo, 2014), a classification of materials that is relevant to the architecture and design professions has been succinctly attempted by Axel Ritter, according to whom "depending on their characteristics, their structure and other properties, materials and substances today can be generally differentiated as" (2007, p.26):

a. Recyclable Materials
b. Biodegradable Materials
c. Biomaterials
d. Nonvariable Materials
e. Functional Substances
f. Smart Materials
g. Hybrid Materials
h. Functionally Gradient Materials
i. Nanomaterials

Based on this classification, the intent of this research will be to address category *h. Functionally Graded Materials (FGM)*[02] that amid all the above-mentioned innovations, have been termed "the holy grail of materials [science]" (Wiscombe, 2012, p.5) and are deemed to have the capacity to bring about radical changes in architecture (Michalatos, 2016; Grigoriadis, 2016; Wiscombe, 2012; Federal Institute for Research on Building, Urban Affairs and Spatial Development, 2011).

1.1.2. Functionally Graded Material- Architectural Relevance

Before outlining the reasons for dedicating a PhD thesis to this material type, one ought to provide a brief overview of what these materials actually are, as well as their historical origin. Prior to this, however, it should be stated that the main relevance of functionally graded materials in architecture is the fact that they are directly related to the notion of the interface, or the place where parts and materials physically attach together.

02 Otherwise known as, and to be additionally termed within this thesis as *multi-materials*.

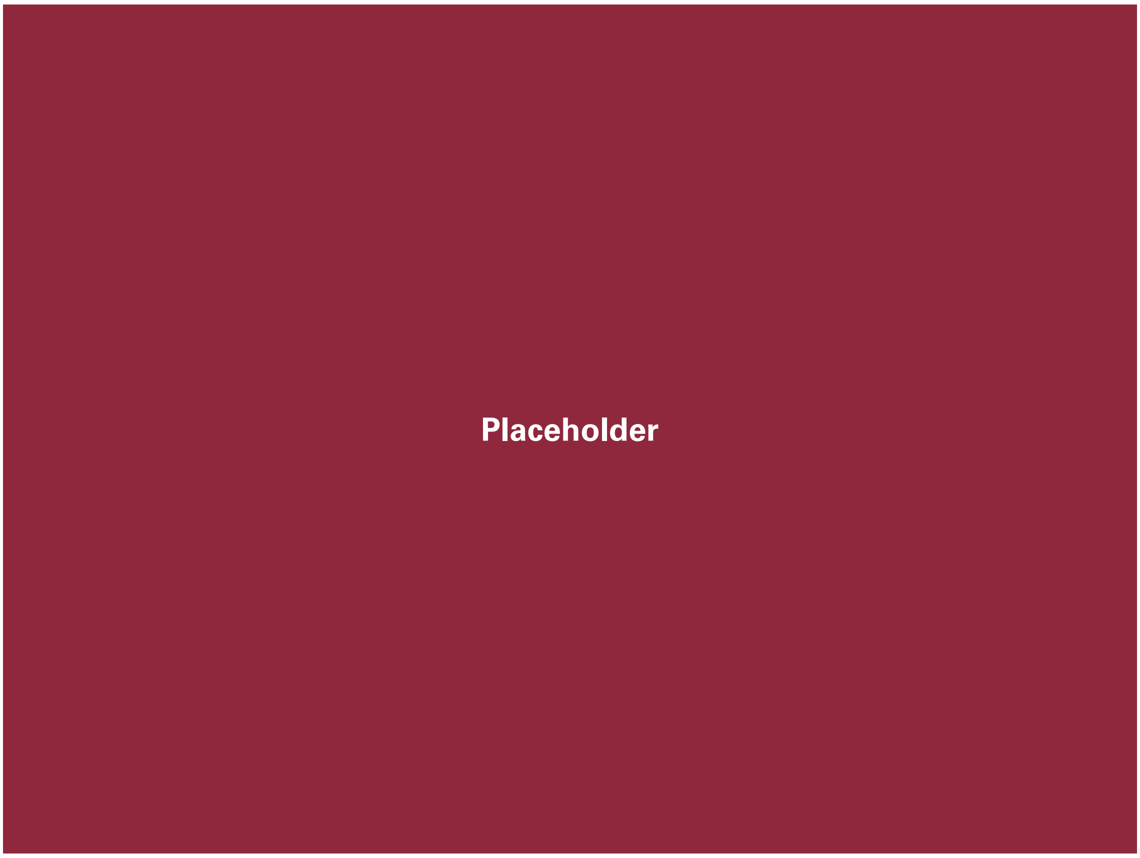

Figure 03: Dovetail Joints, used to connect a series of timber elements. According to Ingold (2015), the pieces in this case are joined but not joined up, the former denoting an open ended connection of sympathy, as opposed to the latter's finality of articulation.

1.2. Historical Context

Going back in time, it was Gottfried Semper who formulated in the eighteen fifties that the way architecture was produced at the time was linked to four different modes of making, namely weaving, moulding, carpentry and masonry (Ingold, 2013a; 2013b; 2015). The latter two categories were subsumed under the larger acts of joining (Figure 03) and stacking, in their turn respectively corresponding to tectonics and stereotomics.

1.2.1. Contemporary Construction Practice

Two hundred years after Semper's writings and quite strikingly, these methods of constructing buildings and structures, as well as the way that the attachment of various elements takes place, are still the same. *Tectonic*[03] *assemblage* i.e. "hammering, bolting and screwing dispa-

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03 The origin of the work tectonic is from the Greek *tekton* (τέκτων) meaning builder, its origin in turn found in the Sanskrit *taksan* "referring to carpentry and the use of the axe (*tasha*)" (Ingold, 2013a, p.19). Semper, according to Tim Ingold (2013a), viewed textiles and carpentry as being complementary techniques, even more so in light of the two words sharing the common root *noc*, whence the German words for knot and joint were derived. Ingold goes on to discuss how joined elements in carpentry should not be seen as *articulated* (consisting of "rigid elements (or blocks) that are linked externally (or *enchained*) side-to-side or end-to-end" (Ingold,

rate elements together mechanically" (Lynn, 2010, p.20) is mainstream construction (Figure 04), while material homogenisation, componentisation and componentry 'collaging' are practices

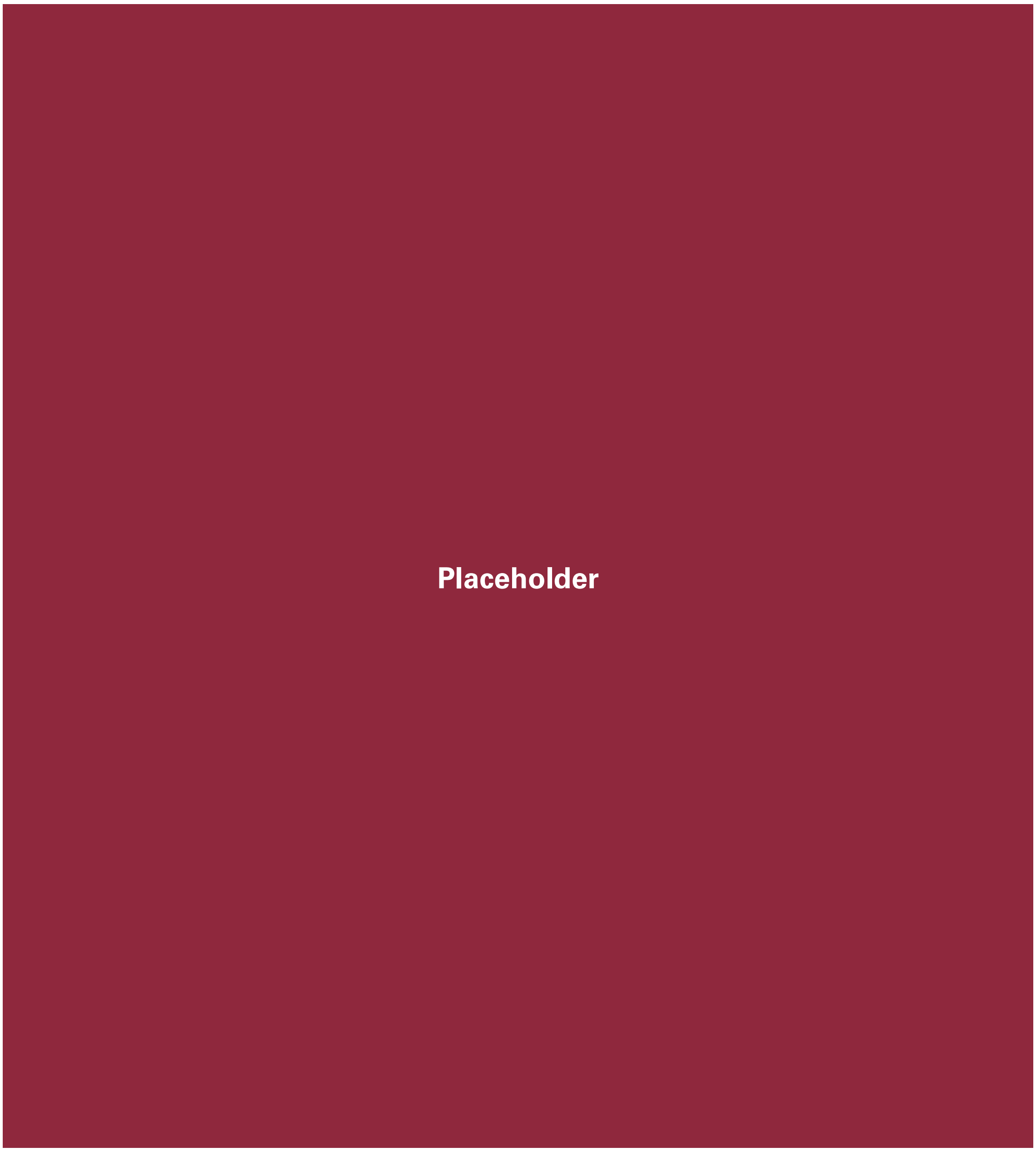

Figure 04: Installed Window Sill Section, showing exterior wall finish, primary and secondary peel & stick flashing, backer rods, wood bucks, lock panel, wood liner, reinforced concrete core, horizontal reinforcement, and interior wall finish.

2013a, p.22)) but rather as knots, coming together through *sympathy* and being connected *in their interiority*, like in the case of mortise and tenon. This of course concerned pieces of the same (wooden) materials put together after they have been cut out to accommodate and fit one another. In contemporary tectonic construction, the different types of materials are typically in their hundreds, joined in all sorts of ways (more often than not, not in their interiorities) and therefore linked in an *articulated* fashion. What will effectively be proposed in this thesis as a way of bringing two or more materials together will be akin to the coming together of *sympathy* or of knotting, but on a chemical level.

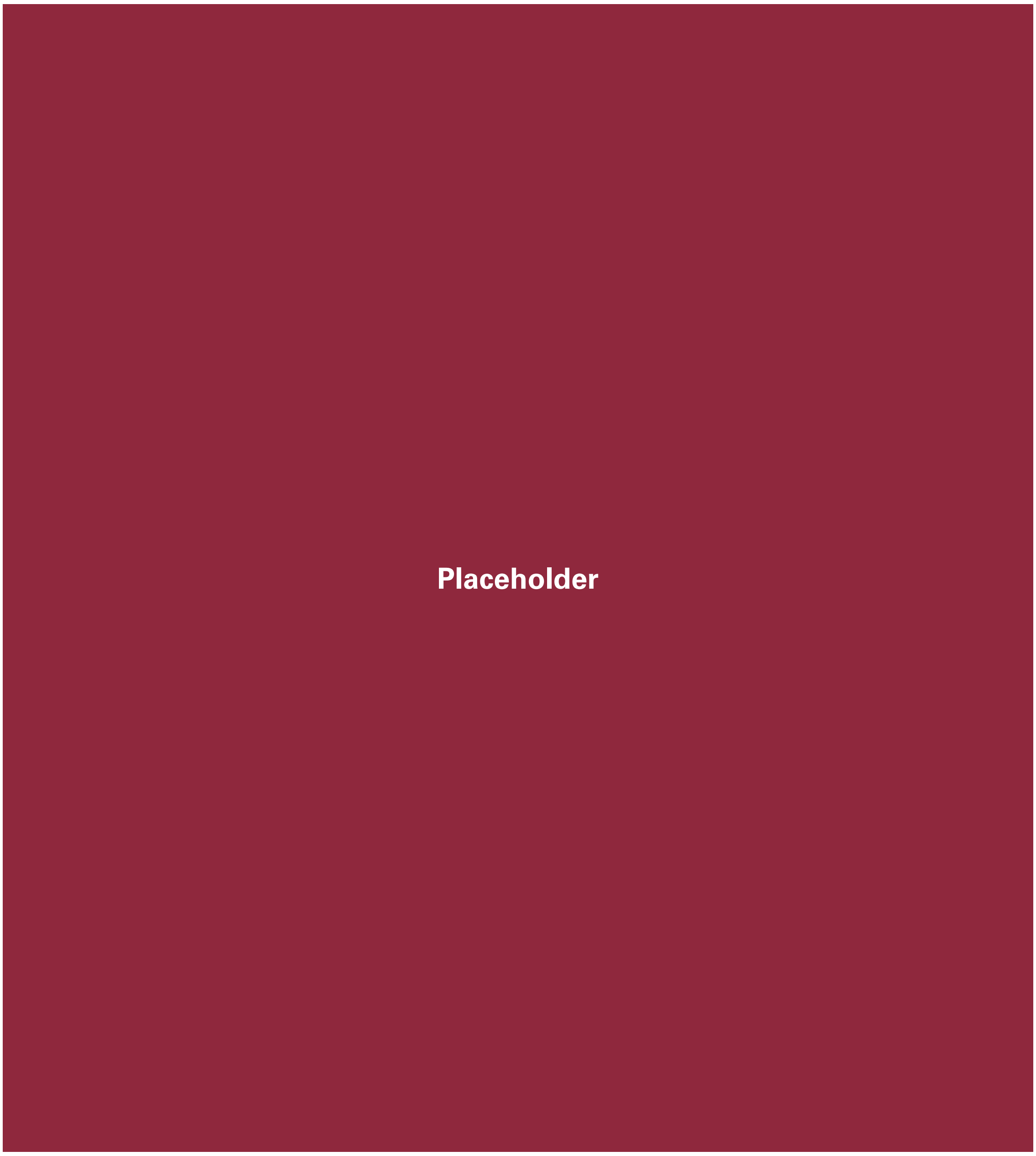

Figure 05: A Stainless Steel Topology Optimised A380 Bracket, (mid-ground) built with direct metal laser sintering offers weight and cost savings when compared to the conventionally manufactured bracket (background).

that have been historically as well as intrinsically linked together and are still exercised today, albeit through increasingly sophisticated construction methodologies[04].

1.2.2. Aerospace Manufacturing Practice

At the same time, in fields adjacent to architecture such as aerospace (the scale of construction being to a very large extent similar to architecture) recent developments have indicated that

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04 An example of this sophistication in the logistics of componentry handling, can be found (among possibly hundreds of others) in the construction of the facade (consisting of 12,000 unique steel alloy panels) of the Barclays Centre in Brooklyn, New York (Gonchar, 2012).

the use of three-dimensional printing results in weight and cost reductions, as well as in the improved structural performance of airplane components that are fabricated as singular pieces. Although still at its nascent stages, the use of additive layer manufacturing in instances like the nacelle hinge of an Airbus A320, typically consisting of welded or bolted components, reduced the weight of the actual part from 918g to 326g (Tomlin and Meyer, 2013), resulting in reductions of approximately ten kilos in the overall weight of the aircraft[05] (Figure 05). In addition, there was also zero wastage in the raw material used for manufacturing the part, as "to produce one kilo of metal, you use one kilo of metal - not 20 kilos" (Morgan, 2013).

1.2.3. Aerospace Manufacturing- Material Palette Expansion

Apart from the use of single materials, when describing the departure of General Electric (GE) from using traditional manufacturing methods and to 3D printing airplane parts, Martin LaMonica (2013) mentions that GE engineers are starting to investigate how the material palette used in the printing process can be expanded. "A blade for an engine or turbine, for example, could be made with different materials so that one end is optimized for strength and the other for heat resistance" (LaMonica, 2013, p.59). Additionally, the MIT Technology Review (2014) article on micro-scale 3D printing started off with the question, "what if 3-D printers could use a wide assortment of different materials… mixing and matching [these material] "inks" with precision?" (Figure 06).

1.2.4. Multi-Materials in Architecture

Effectively, this gradual shift towards the use of mixed materials by the world's largest manufacturer of jet engines, as well as the capability to manufacture bi-materials even by conventional manufacturing methods, suggests that as the environmental and performance benefits are becoming more evident and their use more prevalent, their widespread application in architecture is only a matter of time. As Tom Wiscombe (2012, p.5) suggests, "for architecture, [...] multi-materials open up the greater possibility of being able to not only customize structural rigidity but also create variable material responses to structural, environmental and aesthetic criteria all at the same time."

1.2.5. Fused Materiality History

Historically speaking, the principle of *fused materiality* is an invention that has existed since time immemorial, with examples such as tin infused copper becoming bronze and giving rise to the Bronze Age and carbon squeezing in-between iron on an atomic level that resulted in what is known as steel (Figure 07). The latter changed architecture by enabling the construction of

05 This also had an impact on the reduction of CO_2 emissions by 40%, over the entire lifespan of the optimised nacelle hinge (EOS (e-Manufacturing Solutions), 2014).

Figure 06: A 3D Printed Multi-Polymer Ink Micro-Scale Lattice, built at the Lewis Lab at Harvard University's Wyss Institute for Biologically Inspired Engineering.

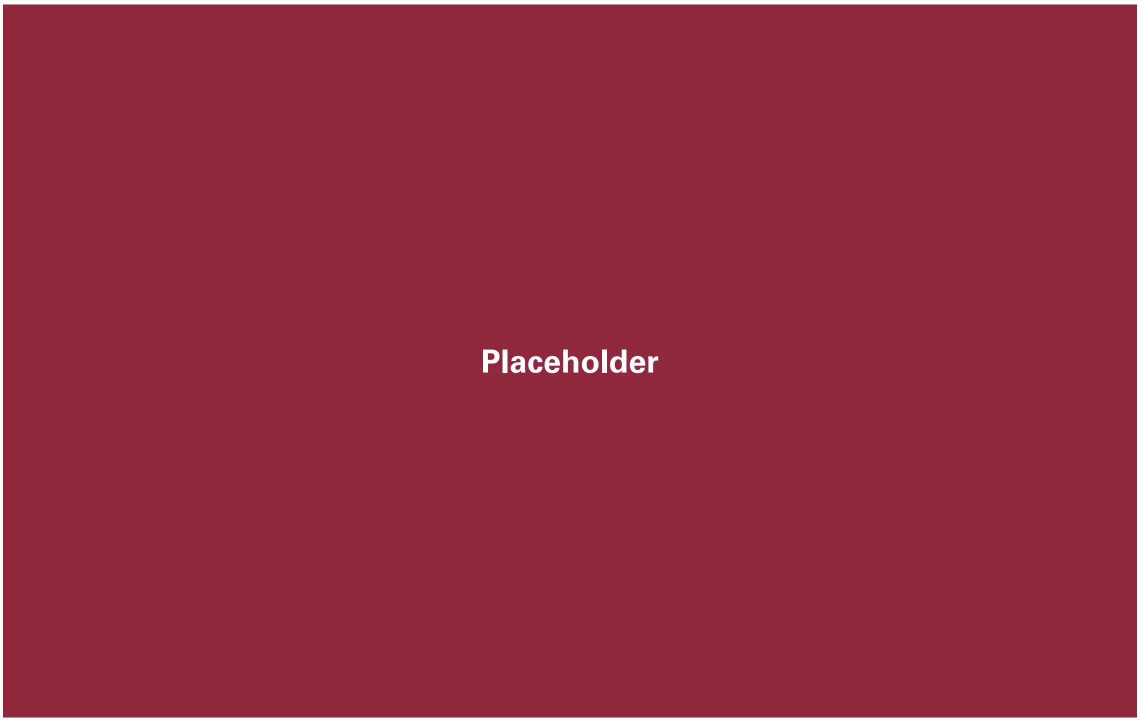

Figure 07: Steel Microstructure. Although a fused material, steel is characterised by a microstructural distribution of steel, carbon, and other alloying elements that is homogeneous. Scale bar on bottom right equals one hundred micrometres.

steel-framed high-rise buildings, subsequently having an immense impact on the organisation of entire cities, as well as instigating certain aspects of the modernist movement along the way (Hitchcock and Johnson, 1997). Although historically fabricated through craft-based processes (DeLanda, 1995), the exponentially advancing material science technologies of today are beginning to allow for targeted control of *material fusion* across different levels that go beyond the aforementioned alloys and towards material gradation on scales that can be visible by the human eye.

1.2.6. Functionally Graded Materials- Origins and Definition

This type of human- and miniature-scale[06] graded materiality was already envisaged by Japanese scientists as far back as the nineteen seventies and effectively realised in the nineteen eighties. More specifically, parallel to the early development and recent widespread usage of composite materials in building and manufacturing, the material science branch of *functionally graded materials (FGM)* was initiated and began to be developed in Japan in 1984. Typically, "composite materials will fail under extreme working conditions through a process called delamination (separation of fibres from the matrix) (Figure 08). This can happen for example,

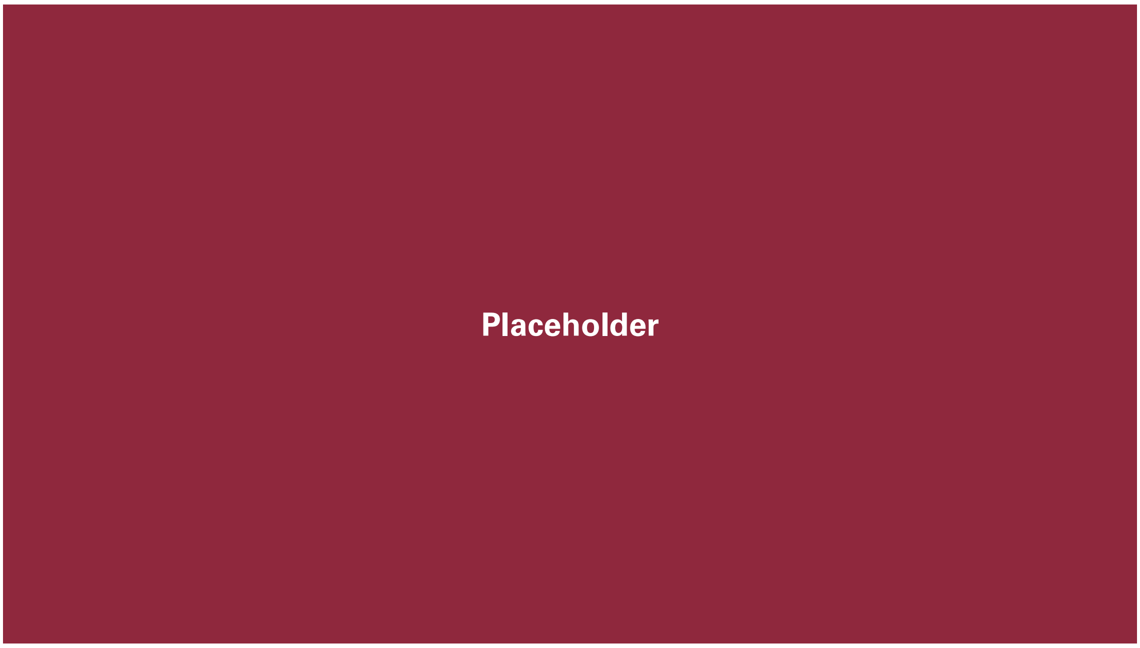

Figure 08: Carbon Fibre Composite Delamination, occurring under edge impact.

in high temperature application where two metals with different coefficient of expansion are used" (Mahamood, et al., 2012, p.1593). Eschewing therefore the use of composites, the scientists solved the problem of very high stresses building up in the connection between the metal-

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06 According to Miodownik (2014, p.239) the "inner space of materials" can be categorised into the following range of scales: atomic (atoms), nano (DNA, nanotubes), micro (cells, crystals), macro (tissue, cellulose), miniature (hair, fabric), and human (hand, cutlery).

Figure 09: 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.

lic and ceramic parts used in hypersonic space planes, by developing a new type of *(functionally graded) material* consisting of ceramic fusing into steel *continuously* over its volume (Figure 09). That way the thermal insulation properties of ceramics were combined with the structural properties of metallic substances, *without* the use of any mechanical fasteners or joining that would compromise the integrity of the material system.

1.2.7. Functionally Graded Materials- Current Applications and Potential Benefits

Fast forwarding to a contemporary context, the main areas of application of FGM currently are in the aerospace, medicine, defence, energy and optoelectronics fields (Birman and Byrd, 2007), as well as in areas such as "cutting tool insert coating, automobile engine components, nuclear reactor components, turbine blade, heat exchanger, Tribology, sensors, fire retardant doors, etc." (Mahamood, et al., 2012, p.1595). Being discerned into two larger groups of surface and volume FGM, for thin sections/surface coatings and for material volumes respectively[07], up

07 All designs in the thesis will be concerned with the latter, i.e. with material volumes and not surface coatings.

until recently these materials ranged from micrometres to a few centimetres when manufactured for research purposes in laboratories, while their industrial application in larger volumes took place in specialized facilities and for applications that were detached from mainstream construction. However, according to 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."

In addition:

> "while the use and application of homogeneous materials allow for ease of production, many qualities – such as improvements in strength, weight, material usage and functionality – could be obtained by the development and application of functionally graded materials at the product and architectural scales [...] it is anticipated that in parallel to the emerging capabilities of multimaterial, freeform fabrication, materials with a wide range of mechanical, electrical thermal and optical properties will soon be seamlessly fabricated." (Oxman, 2012, p.93)

In terms of the benefits that such developments can have, these are summed up by the fact that:

> "The building industry is responsible for 40-50 per cent of resource consumption, 35 per cent of CO_2 emissions, and 50 per cent of waste generation worldwide. It therefore carries the greatest responsibility, but at the same time wields the greatest leverage over the development of a sustainable way of life. Through the development of building components made of functionally graded materials, the building industry can make a significant contribution to reducing resource consumption, energy use, emissions, and waste." (Teknik og Viden, 2011)

Other recent research initiatives similarly indicate that the transfer of the idea of graduating materials from fields such as aerospace engineering to the construction industry can enable savings in both energy and material quantities, while eliminating the formation of weak points in the places that parts would connect in a conventional manner (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, at the moment through the fabrication of small scale representational multi-materials, with research however, already conducted towards a much wider application of functionally graded materials 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).

1.2.8. Shift from Tectonic Construction

The assimilation in the field of architecture and construction of these novel materials and manufacturing technologies and of the corresponding making practice has also been heralded in Greg Lynn's (2010, p.20) statement that "there is a sea change in the world of construction: the shift from assemblage to *fusion* [emphasis added]. In material terms this translates into a move from mechanical to chemical attachments; more simply, things are built without bolts, screws, nails, and pegs." In addition, Lynn (2010, p.13) goes on to describe the inspiration instigated "by the aesthetic of these composite materials that are combined into continuous surfaces [...] we defined a new composite paradigm that is in contrast to the much more familiar tectonic paradigm for architectural design."[08]

Departing or rather adding to Semper's modes of making the research therefore proposes and focuses on a fifth category, relevant to this twenty first century material paradigm, that of *fusing* (Figure 10).

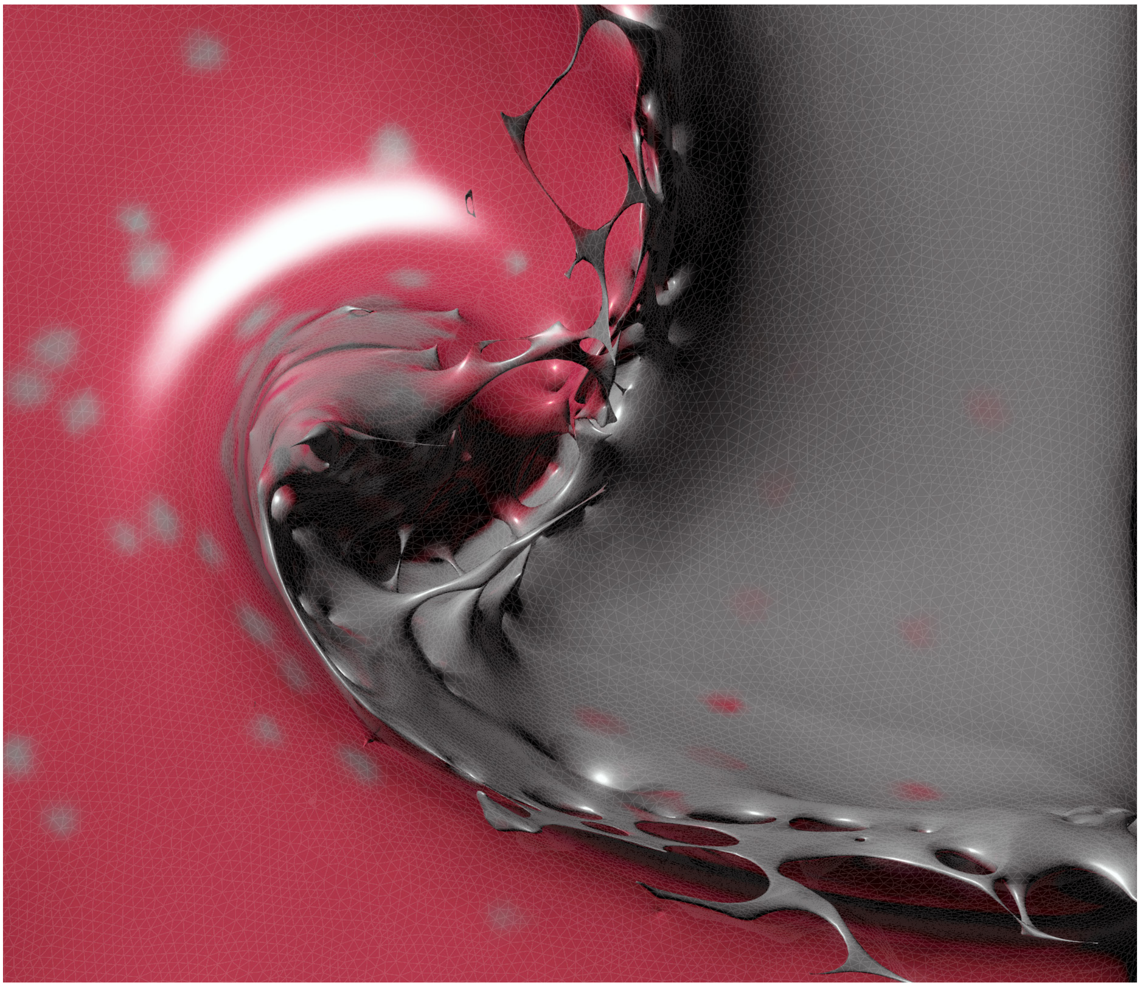

Figure 10: Computer Rendering of the Fusion of Two Liquids.

08 Here, Lynn is referring to composite materials, however, replacing the term composite with fused can be equally valid as it can be logically supported in the context of the sentence and the paragraph and text beyond.

1.3. Research Question

1.3.1. Anticipated Impacts of Graded Material Use in Architecture

Additionally, 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 building components, will progressively be superseded.
b. *Fusing* will become the appropriate building technique linked to this twenty first century material paradigm.
c. Discrete boundaries will be replaced by *gradients*.
d. The acceptable margin for error will increase, as gradients are by definition more 'forgiving' than discrete components.
e. Designing and building will effectively be made with materials directly.
f. There will be a shift towards a new design process in which material behaviour is prioritized.
g. Procedures of translation between two and three dimensions, in which 3D CAD information is typically converted into 2D (drawn) instructions that then get converted again into built 3D space, will be superseded.
h. Concepts of composition previously based on discrete geometric elements will effectively have to be rethought.

1.3.2. Main Thesis Research Question

As this is a PhD by Project investigation, the focus of the thesis will primarily be on points *e.*, *f.*, and to a much lesser extent on point *g.* (in subchapter 5.2.). In effect, the main research question that the following will be addressing in response is, *what is the appropriate design methodology that can correspond to the use of functionally graded materials in architecture?*

1.4. Main Term Definitions

1.4.1. Methodology Definition

According to the Merriam-Webster dictionary, the term *methodology* is defined 1. as "a body of methods, rules, and postulates employed by a discipline; a particular procedure or set of procedures" and 2. as "the analysis of the principles or procedures of inquiry in a particular field." The definition of the word that will be followed here is namely the one of "particular procedure." However, as it will be evident later this procedure is by no means one that is "rigid, inflexible, and with limited application" (Achten, 2003, p.74) as it has tended to be considered as, but rather a framework that is "more *descriptive* than *prescriptive*" (Spuybroek, 2011 cited in Ingold, 2013a, p.55).

1.4.2. Epistemology Definition

Additionally, another term that ought to be explained, which also relates to the title of thesis is the *epistemology* around this novel methodology. Epistemology is defined as "the study or a theory of the nature and grounds of knowledge especially with reference to its limits and validity" or more succinctly as the "understanding of the process of knowing" (Capra, 1996, p.39). As it will be evident, formulating one will be necessary in light of the *material simulations* that will form the main design tool for attaining material fusion.

1.5. Practice-Based Aims & Objectives

1.5.1. Main Thesis Objective

Effectively, and in regards to the research question and to the aforementioned points *e.* and *f.*, the *first objective* of the thesis will be to *propose a novel step-by-step*[09] *methodology/workflow of designing with functionally graded materials.*

1.5.2. Anticipated Research Audience

Additionally, answering the initial point made in the beginning of this chapter, concerning the reasons for dedicating a PhD thesis to this novel material type, the main claim when considering the above as evidence is that multi-materiality is an unavoidable reality in architecture and it is only a matter of time for it to be manifested more concretely[10]. Anticipating this new reality, the thesis will in effect lay 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.

In addition, as it will be evident later, this change will also instigate a new way of thinking *during* design that will stem directly from the cognitive processes involved in this direct involvement with *virtual* and *mental materials*. Consequently, the investigation regarding these processes can be useful to cognitive and material culture theorists conducting research into the cognitive processes involved in new forms of design pursuits.

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09 The term *step-by-step*, is related here to the format that the methodology will be presented at and should not be associated with the aforementioned *articulation*, or a compartmentalised, linear process of design. The case in support of this avoidance of compartmentalisation will be evident in the main chapters that follow.

10 Four built examples of this manifestation are mentioned in the conclusion.

1.5.3. Sub-Objective 01

In terms of a specific focus, this workflow will be concentrated on designing the connection of glazing to the aluminium frame in a curtain wall envelope and will be concerning the whole process from beginning to end, of research, design, and fabrication of the connection. Effectively, a *second objective* will be to *fabricate the redesigned connection in a physical multi-material*.

1.6. Architectural & Design Definitions

1.6.1. Curtain Walls

Here, and before proceeding further, there needs to be a clarification in regard to the type of tectonic interface that will be the focus of the design operation, as well as the reasons for selecting this as the main element to redesign. What will be presented in the following in effect, are the problems associated with it and how the subsequent resolution of some of these will form a first set of criteria against which to evaluate the design 'output'.

As mentioned, the methodology will be applied in the design (using a functionally graded material) of a curtain wall segment. The definition of this is as such:

> "Curtain walling may be defined as being non-loadbearing walls, usually suspended in front of a structural frame, their own deadweight and wind loadings being transferred to the structural frame through anchorage points. Usually they consist of a rectangular grid of vertical or horizontal framing with infill panels of glass or some other lightweight panel…" (Brookes, c1998, p.148) (Figure 11)

The reasons for selecting this type of building element in order to apply and examine the multi-material design workflow through, relate to parameters that are both technical and procedural, as well as to ones that are architectural and design theory-related.

1.6.2. The Problems with Curtain Walls

Analysing the technical aspects in more detail, this type of system is associated 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 and according to Jane Anderson (2009, p.36) 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", as well as the same summary rating in the overall category average for cladding and framed construction. In general, the sources of some of these problems can be pinpointed *a.* in the extraction and processing of the raw materials that the different subparts of a panel are made of, *b.* in the techniques employed to fabricate these

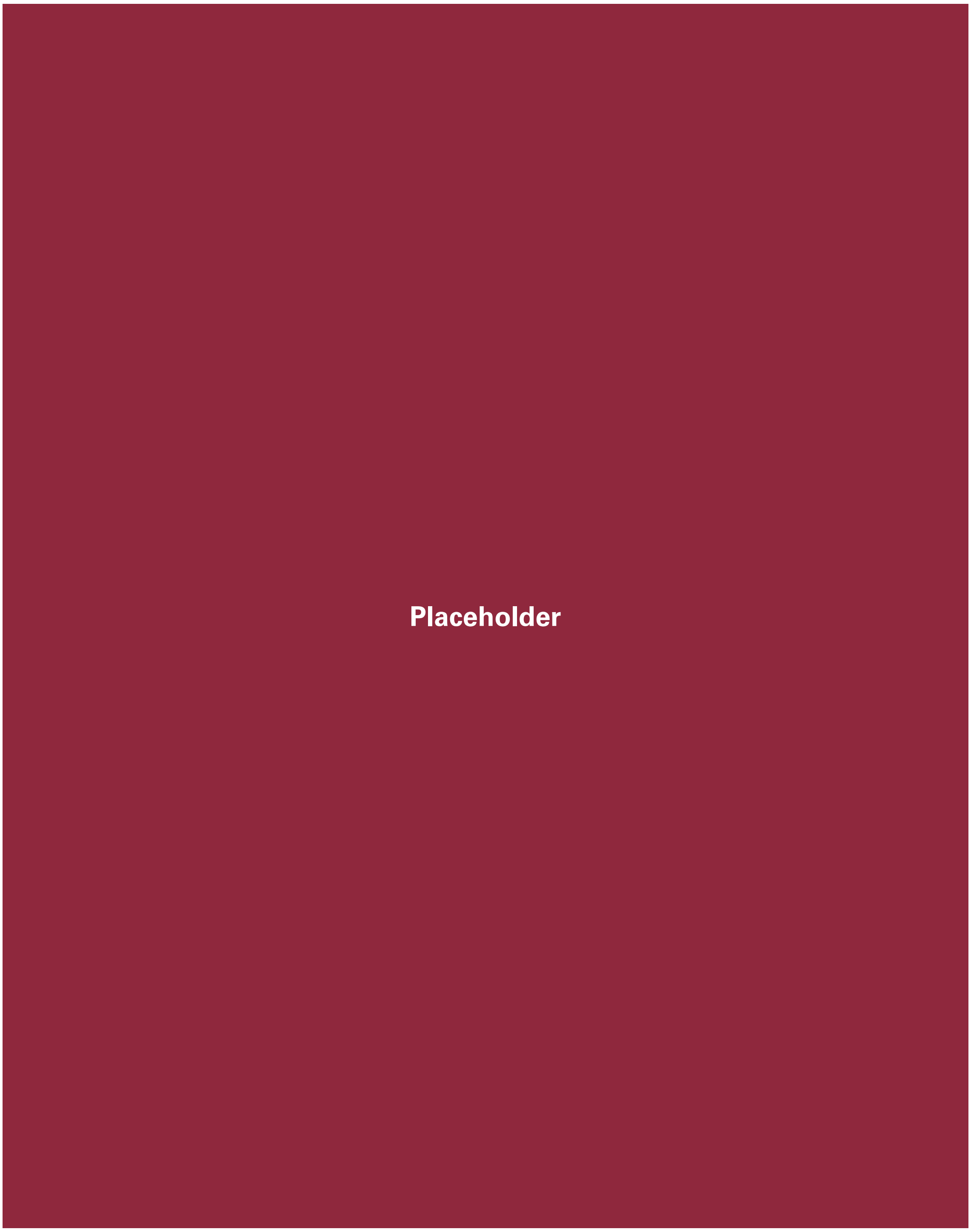

Figure 11: The Mega-Suspended Curtain Wall of the Shanghai Tower by Gensler, consists of an external skin behind which are ventilation atria and an interior second skin. The buffer area created in between these, regulates the air temperature and contributes to the building's climatic control.

constituent parts, and *c.* in how the resulting panels are procured, assembled and installed in a building.

1.6.2.1. Materiality

Starting off with point *a.*, the materials that make up a cladding panel consist of aluminium, silicone, polyetherimide, EPDM (ethylene propylene diene polymethylene) rubber and insulating glass. The raw materials that these are extracted or synthesized from are typically sourced in remote parts of the world, following messy procurement routes that involve tens or sometimes hundreds of different trades (Wiscombe, 2012, 2010) and are processed through immensely energy-consuming methods. One could in fact dedicate a whole PhD thesis to providing a detailed and in-depth step-by-step analysis of these delivery routes and the vast networks of associated processes that all have a negative impact on the environment and beyond. As this is not the scope of this present thesis, however, the intent has been to solely highlight the current problems associated with the curtain wall envelope in order to eventually demonstrate how the use of a multi-material that can be additively manufactured, as well as the analysis at a later stage of the cognitive processes taking place during the design of this multi-material, will be addressing some of these technical and theoretical issues.

1.6.2.2. Manufacturing Processes

Moving on to the level of manufacturing and regarding point *b.*, some of the methods employed in fabricating the different subparts of a panel include low pressure die casting, injection moulding, anodizing, and powder coating (Figure 12). Looking into these individually, low pressure die casting is utilized to produce the components made of aluminium that are then powder coated for the mullions and transoms, and 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 (as "tools have to be made in steel to be able to withstand the temperature of the molten alloys" (Thompson, 2007, p.127)) it "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 gasket and glazing sealant modules, involves the feeding of molten material by an Archimedean screw via a barrel canister into a mould cavity within which the substance cools down and is subsequently removed when it has solidified. In a similar manner to die casting, the procedure requires the use of material in high temperatures and pressures, as well as entailing 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).

Further down the line, once the aluminium mullion and transoms have been generated through die casting, a powder coating application ensures their protection from damage and eventual corrosion. This operation in its turn utilizes thermosets such as "epoxy, polyester, acrylic, and hybrids of these polymers" and/or thermoplastic powders consisting of "polyethylene (PE), polypropylene (PP), polyamide (PA), polyvinyl chloride (PVC), fluoropolymers and many more" (Thompson, 2007, p.359). It is evident in this case that the five basic materials that make up a panel are the visible end of a process that involves many other substances utilized in various states from molten to solid, which are all synthetic and to their vast majority highly toxic. Lastly, the aluminium glazing lining is anodized in order to create an oxide layer that protects the material. The fact that "acidic chemicals are used in the anodizing process" (Thompson, 2007, p.363) is further evidence of the toxicity of the operation.

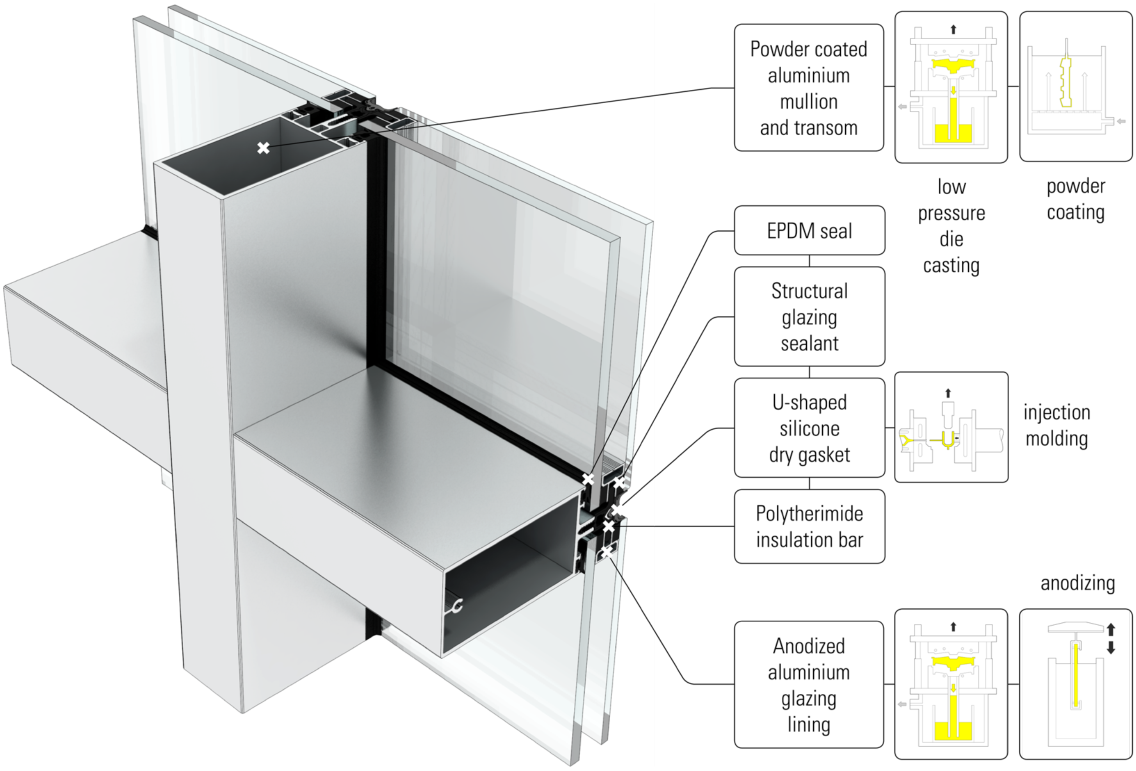

Figure 12: Curtain Wall Detail 3D, indicating the components and materials that make up the envelope, as well as the corresponding manufacturing processes through which these are fabricated.

1.6.2.3. Assembly

On an assembly level and in regards to point *c.*, conventional curtain walls typically consist of "the components of cladding most likely to fail according to the qualitative survey (CWCT 1997c)" (Layzell, 1997, p.175). Karol Kazmierczak (2010, p.5) also states that the "interactions between building facades and structure are notoriously disregarded in the design phase [...] [with this oblivion] manifested in field failures, ranging from persistent leaks of inadequately designed seals to rare but spectacular collapses caused by inadequate joinery" (Figure 13). Furthermore, "poor performance of curtain wall[s] is often due to misunderstanding of fundamental principles of facade design and structural concept of curtain walls by construction parties, and gaps of oversight and coordination in the established project delivery routines" (Window and Facade Magazine, 2016, p.45). This lack of coordination between the various groups involved in this process stems from the fact that the:

> "Architecture of the last 100 years has primarily been understood in terms of frame-and-skin logic. That is to say, structure and skin are highly specialized and

Figure 13: Temporary Plywood Panels Covering the Facade of 200 Clarendon (John Hancock Tower) in Boston. The use of innovative but untested blue reflective glass in the tower resulted in the catastrophic failure of the windowpanes that were detached from the facade and crashed to the surrounding pavements. Plywood panels were effectively used during the replacement of all 10,344 window panes of the building. An eventual independent study showed that the failure occurred due to the expansion of the air in between the two glazing panes putting pressure on the outer glass, which due to its highly stiff connection to the pane could not absorb the forces and was decoupled from the facade.

> only weakly correlated. It was a problematic idea from the start—reductively *anthropocentric* [emphasis added] ... Each is specialized and independently functioning, and is designed and built by separate organizations, often in a process of chaos and conflict. This state of affairs is supported by the international construction industry, which is based on ever-more specialized trades and contracts all the way down to packages such as 'miscellaneous metal'." (Wiscombe, 2012, p.1)

1.6.3. Anthropocentricism and Modernism

Regarding this idea of *anthropocentricism* and in terms of the aforementioned architectural and design theory aspect, the initial development of curtain wall systems through means of mass production and standardization and the opportunities for new architectural and formal expression that this technology offered, meant that they came to be fundamentally associated with modernism and the international style (Window and Facade Magazine, 2016; Hitchcock and Johnson, 1997).

> "As Le Corbusier and others began to claim in the early twenties, mechanization was changing the world, and architecture had to rise to the challenge. *Architects should invent new architectural forms* [emphasis added], made to

measure for the new tools of mechanical mass production; and town planners should invent new urban forms, made to measure for the new tools of mechanical mass transportation." (Carpo, 2011, p.13)

1.6.3.1. International Style- Main Principle

This premise of form-driven, architectural and effectively stylistic novelty was partially due to the fact that the curtain wall allowed for the architecture-as-mass principle that had been the norm historically to be superseded in the early nineteen twenties by the one of architecture-as-volume. In this case, the large-mass, load-bearing exterior wall of the past gave way to the disengagement of structure and skin, with the curtain wall forming a mere carapace to the building. The ensuing voluminous open box effectively replaced the density of the brick wall and became fundamental to the international style as the "prime architectural symbol" (Hitchcock and Johnson, 1997, p.56).

1.6.3.2. International Style- A Form & Composition Bias

Correspondingly, the design focus shifted to a *form centric* approach of achieving elevational plane and surface continuity[11] and of attaining the volumetric effect of the open box. Curtain wall mullions and transoms consequently became of primary regulatory importance as the employment and *composition* of these linear elements in elevation and of column grids in plan, was key to achieving this effect of the uninterrupted plane (Hitchcock and Johnson, 1997).

1.6.3.3. Material Homogenisation

More interestingly, and in terms of this type of tectonic element's material makeup that relates directly to the main subject matter of the thesis, according to Hitchcock and Johnson (1997, p.61) "light simple frames, preferably of durable non-corroding metal in standardized units, [were] to be desired as much aesthetically as practically." In terms of the composition of these metal parts, as Manuel DeLanda (1995) states:

> "while naturally occurring metals contain all kinds of impurities that change their mechanical behaviour in different ways, steel and other industrial metals have undergone in the last two hundred years an intense process of uniformation and homogenisation in both their chemical composition and their physical structure […] only then the full efficiencies and economies of scale of mass

11 This importance of continuity of surface is something that is also prevalent in the ship and automotive design industry, albeit for functional reasons, and will be discussed further in subchapter 4.1.1.

production techniques could be realised. But this homogenisation also affected the engineers that designed structures using these well-disciplined materials.”[12] (Figure 14)

Figure 14: Aircraft Assembly at the Bell Aircraft Corporation Plant in New York. Apart from material homogenisation that made the behaviour of each component more predictable and the assembly process more streamlined, as it will be seen in 4.1.2., the description of the parts contained within the aircraft became more precise, necessitating an equally precise design of the containing vessels.

1.6.3.4. International Style- An Anthropocentric Bias

This standardized nature of the mass-produced parts effectively meant that the materiality of the envelope itself was taken as a given, with this unquestioning being another parameter that contributed to the architectural design focus shifting to proportion, regularity, rhythm and sizing.

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12 This quote is referring to the initially heterogeneous, raw extracted material being converted into one that is uniform. The proposed design methodology will still be utilising homogenized individual sub-materials, which, however, are then admixed to generate heterogeneous multi-material compositions. In this respect, there can be a whole new area of a technical investigation in which the viability of utilizing partially treated aluminium (i.e. where aluminium conversion from raw bauxite does not go through all the environmentally hazardous processes for obtaining the material in its pure form, but is stopped midway where some of the ‘impurities’ are preserved, so as to reduce the environmental damaging) is examined.

In effect, this strengthened even further the centrality of the role of the "ingenious architect" (Hitchcock and Johnson, 1997, p.74) who worked with principles of top down regularity towards this phenomenological "achieving [of] brilliant effects with the limited means" (Hitchcock and Johnson, 1997, p.79) (Figure 15).

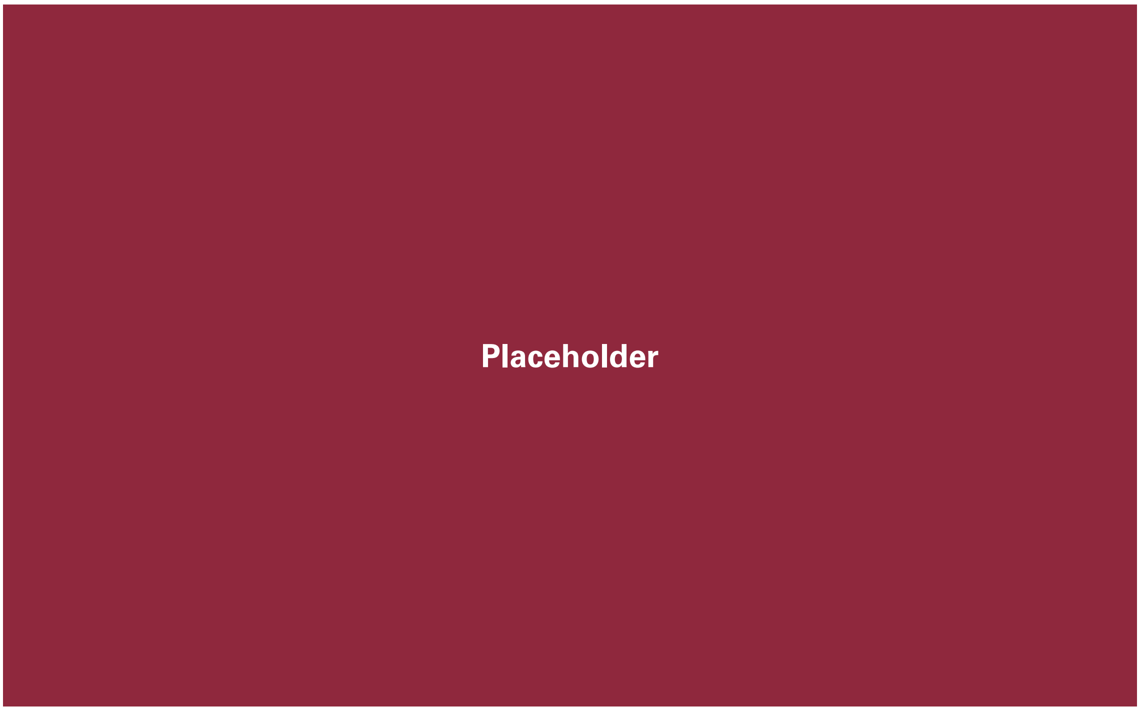

Figure 15: Bauhaus Dessau Living Quarters (foreground) and Administration and Class Rooms Building (background) by Walter Gropius. According to Hitchcock and Johnson (1997, p.143) "the separate wings, each with a different function—living quarters, classrooms, workshops—are skilfully composed. The checkerboard window arrangement of the living quarters contrasts with the ribbon windows of the classrooms and administrative section. An example of different functions emphasized by a different handling of regularity. The supports of the centre section are awkward in shape."

Eventually, what formulated the main means of ideological expression in various buildings and structures during the early years of modernism became standard practice in the years beyond, with the use of this type of framed envelope construction still prevalent today. Albeit now disengaged from stylistic or ideological principles, the curtain wall can still be considered a symbol and artefact of the subjective bearing of agency and of the *hylomorphic*[13] tradition so prevalent in architectural discourse.

Here, it ought to be mentioned that this anthropocentric idea of agency is something that this thesis will be arguing against[14], with the relevant argument presented extensively in chapter 4. The discussion will effectively shift to defining the locus (as opposed to the subject) of agency together with the intra-, as well as extra- material forces that are part of the design process in which "forms become contingent, organs are no longer anything more than intensi-

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13 The word is derived from the Greek terms matter, wood, i.e. *hyle* (ύλη), and form, i.e. *morphe* (μορφή). It will be expanded upon in subchapter 1.8.2.

14 The reasons for going against this are presented in subchapter 6.3.1. of the conclusion.

ties that are produced, flows, thresholds, and gradients.... it [will effectively be] a problem not of ideology, but of pure matter" (Deleuze and Guattari, 2004, p.183).

1.6.3.5. The Question of Agency

To further illustrate this move from the question of *who* bears the agency to one of *where* is the agency located, it is relevant to briefly discuss Ingold's (2013a, p.20) example of drawing two continuous parallel lines, one representing the flow of consciousness "saturated as it is by light, sound and feeling" and the other representing the flow of materials i.e. their various states and interactions as they circulate within the world (Figure 16). Imagining that a point is placed on each of these trajectories, the stoppage taking on the semblance of an *image* in the line of consciousness and of an *object* in the line of material flows, an arrow drawn to connect the two represents the typical connection that exists between image and object and that needs to be rethought. Similarly, the aim in this respect will be to switch one's object-oriented, anthropocentric "perspective from the endless shuttling back and forth from image to object and from object to image" to "the material flows and currents of sensory awareness in which images and objects reciprocally take shape." Or as Anthony White (2016, p.214) states when analysing

Figure 16: Ingold's diagram of the flow of consciousness and of materials.

the sculpture *Untitled* (1967) (Figure 17) by Arte Povera artist Giovanni Anselmo[15] "rather than a relationship of proportion or balance between […] components" to perceive "the artwork's contingency in relation to extra-aesthetic forces, including gravity and the nature of the floor on which the sculpture sits."

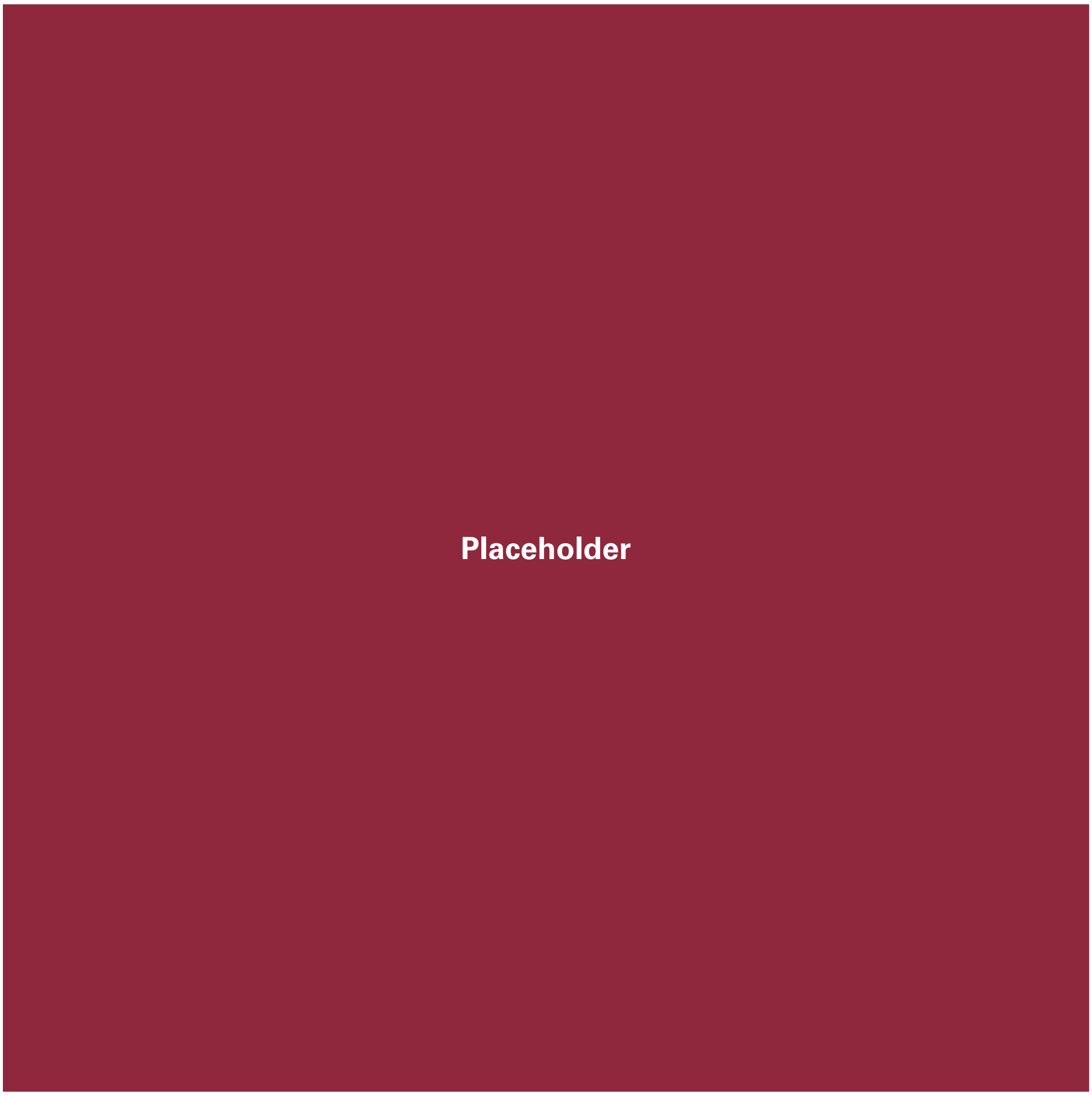


Figure 17: Giovanni Anselmo's *Untitled*, 1967, removes the artwork from its 2D surrounding frame and places it inside the gallery space. A wooden box covered in black Formica is placed on top of another box of the same material and dimensions, with metallic wedges placed in between the two. The wedges level the top box, with this levelling being evident through a spirit level embedded in the artwork. These various parts make the viewer aware of the relation of the artwork to its wider context and conditions of the gallery space.

15 In the same article discussing Alberto Burri's work, whose artwork *Combustione Plastica* will be used as a key reference in 4.3.7.4.

1.6.4. Sub-Research Question 01

Going back to the cladding interface and regarding the technical details of the type of envelope, part of which will be redesigned, these have been set out in collaboration with Iain Bleakley, Senior Facade Engineer at AKT II Envelopes and have also been input in performing the structural analyses (Bleakley, 2016) that are presented in 3.3.7.1. Specifically, the main assumption will be 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 will be to redesign the point where the glazing connects to the aluminium frame (Figure 18), while preserving the structural and optical qualities of the original panel. Effectively, a second sub research question here will be *how can a building skin to structure connection be designed with a functionally graded material*.

To conclude, it should be stated that in terms of the aforementioned technical and procedural issues (namely regarding the issues of efficiency and operational adequacy and briefly the one of sustainability), these will be automatically addressed by reducing the amount of materials in the connection and by arguing for the use of an alternative manufacturing method in the fabrication of the redesigned curtain wall segment. In terms of the architectural and theoretical issue, this has been briefly outlined in the previous paragraph, with a further analysis following in the next subchapter and the full argument against it extensively discussed and presented in chapter 4.

1.7. Theoretical Aims & Objectives

1.7.1. Sub-Objective 02

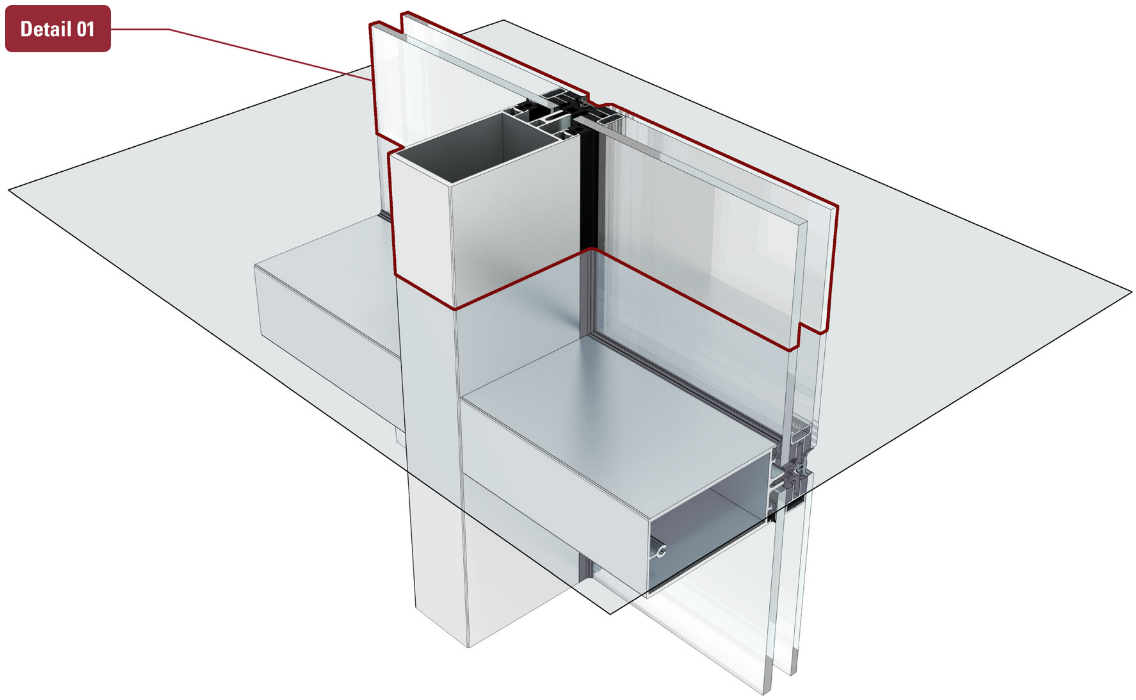
Carrying on, a *third objective* of the thesis will be to *demonstrate the enmeshed correlation between form and materiality*, enabled here by the use of multi-materials.

1.8. Theoretical Definitions

1.8.1. Theoretical Focus

As previously mentioned, the use of graded materials in architectural design and multi-material research in general are nascent areas of investigation, with a direct consequence of this being the absence of any current theoretical discourse related to this field. At the same time and in advance of what will follow, there is the requisite of defining the theoretical niche that the thesis will be operating within. Here, this will relate to the latter part of the word multi-*materiality*, namely the wider encompassing term *materiality* and its theoretical counterpart of *materialism*.

More specifically, this outlining will be made within the ongoing new materialist discourse that according to Diana Coole and Samantha Frost (2010, p.8) is discerned by an "insist-



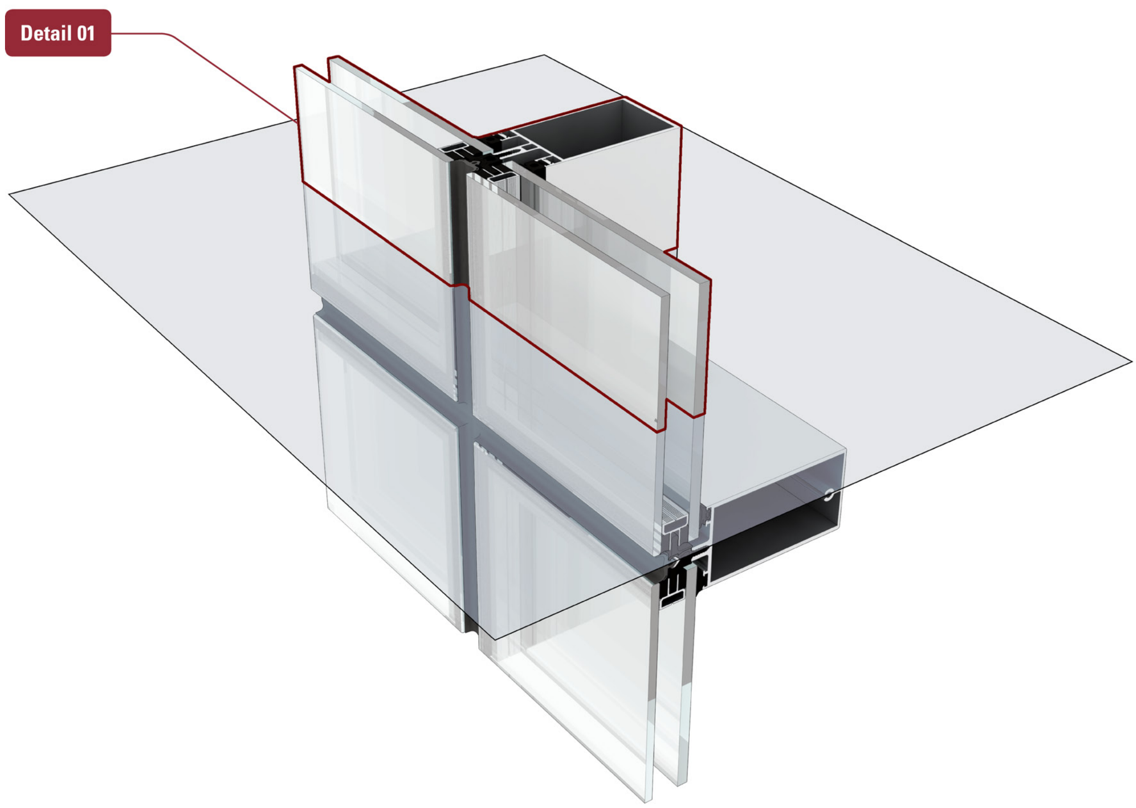


Figure 18: 3D Renders of model FW 50+SG from the Schüco Facade System Catalogue, showing in red the detail that will be redesigned in what follows.

ence on describing active processes of materialization of which embodied humans are an integral part, rather than the monotonous repetitions of dead matter from which human subjects are apart." With this statement as a starting point, there will be a series of clarifications made in what follows about the specific type of materiality referred to in the research, as well as the theoretical work that will underpin this. But prior to that it is worth mentioning the origin of it all.

According to Fritjof Capra (1996, p.80), "the study of substance began in Greek antiquity in the sixth century BC, when Thales, Parmenides, and other philosophers asked: What is reality made of? What are the ultimate constituents of matter? What is its essence?"

1.8.2. Hylomorphism

Following up on this inaugural discourse on substance, the "dead matter" of the initial statement can be traced back to Aristotle who was the first in the western philosophical tradition to put forward the distinction between body and soul. Effectively this formed the origin of the wider philosophical disjunction between matter and form. "Any substantial thing, Aristotle had reasoned, is a compound of matter and form, which are brought together in the act of its creation"[16] (Ingold, 2013a, p.37). According to Ingold (2013a, p.37), in that reasoning, lay "the foundation of the hylomorphic model of making" of artefacts that is equivalent to the imposition of "forms internal to the mind upon a material world 'out there'" (Ingold, 2013a, p.21). This, was the basis of the *hylomorphic* thinking that became embedded in the subsequent history of western thought. Here, this concept will formulate a central problem that will be discussed more extensively in chapter 4. and is a doctrine that will be argued against.

1.8.3. Contemporary Materiality

Going through its Cartesian reiteration (Malafouris, 2013; Coole and Frost, 2010) in the seventeenth century, this notion of inactive, submissive matter found a suitable scientific underlay in Newtonian physics that set out the linear cause and effect rules for calculating and understanding the corresponding physical phenomena (Coole and Frost, 2010). Fast forwarding this to the twentieth century and beyond, what started off as the first description of atoms in 1905[17] has nowadays escalated to a point where discoveries in contemporary physics are beginning to invalidate some of the assumptions of classical Newtonian physics. Indicatively, in the field of quantum physics, the discovery of the existence of subatomic particles as the units that make up the atoms themselves means that "matter is [nowadays] described as being composed of two kinds of particle, quarks and leptons, which together compose fermions" (Coole and Frost, 2010, p.12). These are considered the essential building block[18] that makes up everything

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16 The original Aristotelian statement can be found in the beginning of the second book of *De Anima*: "Now there is one class of things which we call substance, including under the term, firstly, matter, which in itself is not this or that; secondly shape or form, in virtue of which the term this or that is at once applied; thirdly the whole made up of matter and form. Matter is identical with potentiality, form with actuality" (Ingold, 2013a, p.144).

17 By Albert Einstein.

18 According to Ingold (2013b) the metaphor of the 'building block' as the primary constituent entity came into existence in the 19th century and is something that should be replaced by the

in the universe, but at the same time, peculiarly, they are not the discrete, stable entities that one would imagine. This is mainly because "the states that constitute them as "particles" are variable", which means that any corresponding "account of matter also requires an inference of short-lived virtual particles that flash in and out of existence, clustering around the more enduring particles whose properties they alter" (Coole and Frost, 2010, p.12). This, effectively changes a very long historical scientific tradition that has been maintaining the instability of matter as one of its central dogmas[19], over to a condition of material oscillating constantly between a Boolean on and off state. In turn, it is also implying a fundamental shift from the *certainty* of "*matter is* [emphasis added]" to the *fluctuation* of "*matter becomes* [emphasis added]"[20] (Coole and Frost, 2010, p.10).

1.8.4. Materialisms

Furthermore, apart from this science driven change in point of view, there is a shift that has been taking place in parallel to the aforementioned Neo-Cambrian explosion of the invention of new types of materials. Namely and importantly here, this is the formulation of a vast spectrum of theories relating to materialist philosophical discourse that consist of a strikingly diverse range of takes on materialism and of what this encompasses. Just to mention a few, Louis Althusser's (1970) materialist thesis concerned the diffusion of the ideological and repressive apparatus of the state within quotidian rituals and practices, while in Jacques Derrida's "materialism as a philosophy of the outside" (Coole and Frost, 2010, p.73) the term matter was dissociated with any spiritualist or ideological connections and acquired a new logocentric significance and value[21]. Additionally, in the fields of anthropology and archaeology, when discussing the

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knot as the fundamental element of building. Strikingly pertinent is also the position that "the block and the knot represent mutually exclusive master-tropes for describing the constitution of the world, predicated on philosophies, respectively, of *being* and *becoming* [emphasis added]" (Ingold, 2013b, p.27). An additional abandonment of the building block is in Chew's 'bootstrap philosophy' that accepted "no fundamental constants, laws, or equations. The material universe [was rather] seen as a dynamic web of interrelated events" (Chew, 1970 cited in Capra, 1996, p.39).

19 Very relevantly here, Jane Bennett (Coole and Frost, 2010, p.62) states that today, "mechanistic models of nature have morphed into systems theory and complexity theory" and "inert matter has been challenged by fluid dynamics and complexity theory."

20 A similar differentiation can be found in Spinoza's *Ethics* between *natura naturata* and *natura naturans*. "*Natura naturata* is passive matter organized into an eternal order of Creation; *natura naturans* is the uncaused causality that ceaselessly generates new forms" (Bennett, 2010, p.117).

21 The reason of this shift in philosophy from a materially centred discourse to the analysis of symbols and texts, is mentioned in 4.2.3.

different takes on the topic of materiality, Ingold (2013a) provides a name-dropping of no less than five different academicians' definitions within the same paragraph[22].

1.8.5. Materialisms in the Thesis

Within this expansive theoretical domain and considering that this research is a design investigation, the term materiality will be understood in its literal sense, initially concerning materials as the stuff that makes up the physical world. As it will be evident hereinafter, however, this term will be extended to also encompass *virtual materiality* (i.e. materials that are computed), as well as *mental materiality* (i.e. materials that are *thought of* or *with*, and are "*co-extensive and consubstantial with mind* [emphasis added]" (Malafouris, 2013, p.77)). Based on the latter, and in response to the hylomorphic model, or what will be discussed later as the dualist ontology of mind and matter, a main point of originality in the thesis is that it will endeavour to *weld together this separation by incorporating the human brain and analysing the related cognitive processes corresponding to the (virtual) (multi-)materials that the designer works and interacts with*. This is due to the fact that although as discussed, the scientific and theoretical discourse on matter has opened up new grounds of investigation resulting from the current discoveries about what a material actually is, in architecture, the "hylomorphic model of creation seems to [still] dominate our understanding of design today" (Gürsoy, 2016, p.851). This is as "the architect would like to think that [a design creation] stands as the crystallisation of an original design concept" (Ingold, 2013a, p.47) i.e. maintaining the dictum of a "[mentally induced] form capable of imposing properties upon a matter" (Deleuze and Guattari, 2004, p.451).

1.8.6. Mind & Brain

Additionally, if one were to be more precise about the use of the term brain, this welding will be made by talking about the *mind* as opposed to the *brain*: "Mind is not a thing but a process – the process of cognition, which is identified with the process of life. The brain is a specific structure through which this process operates" (Capra, 1996, p.271) (Figure 19). Furthermore, and framing the interdisciplinary conversation in the thesis that will incorporate certain aspects of cognitive theory[23], it will be proved that the aforementioned separation of form and material cannot be sustained at any point of the proposed design workflow.

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22 Put forward by Christopher Tilley, Andrew Jones, Nicole Boivin, Paul Graves-Brown and Joshua Pollard.

23 Namely the use of Conceptual Blending (Fauconnier and Turner, 1998; 2002), Material Anchoring (Hutchins, 2005) and Material Engagement (Malafouris, 2008; 2013; 2014) theories.

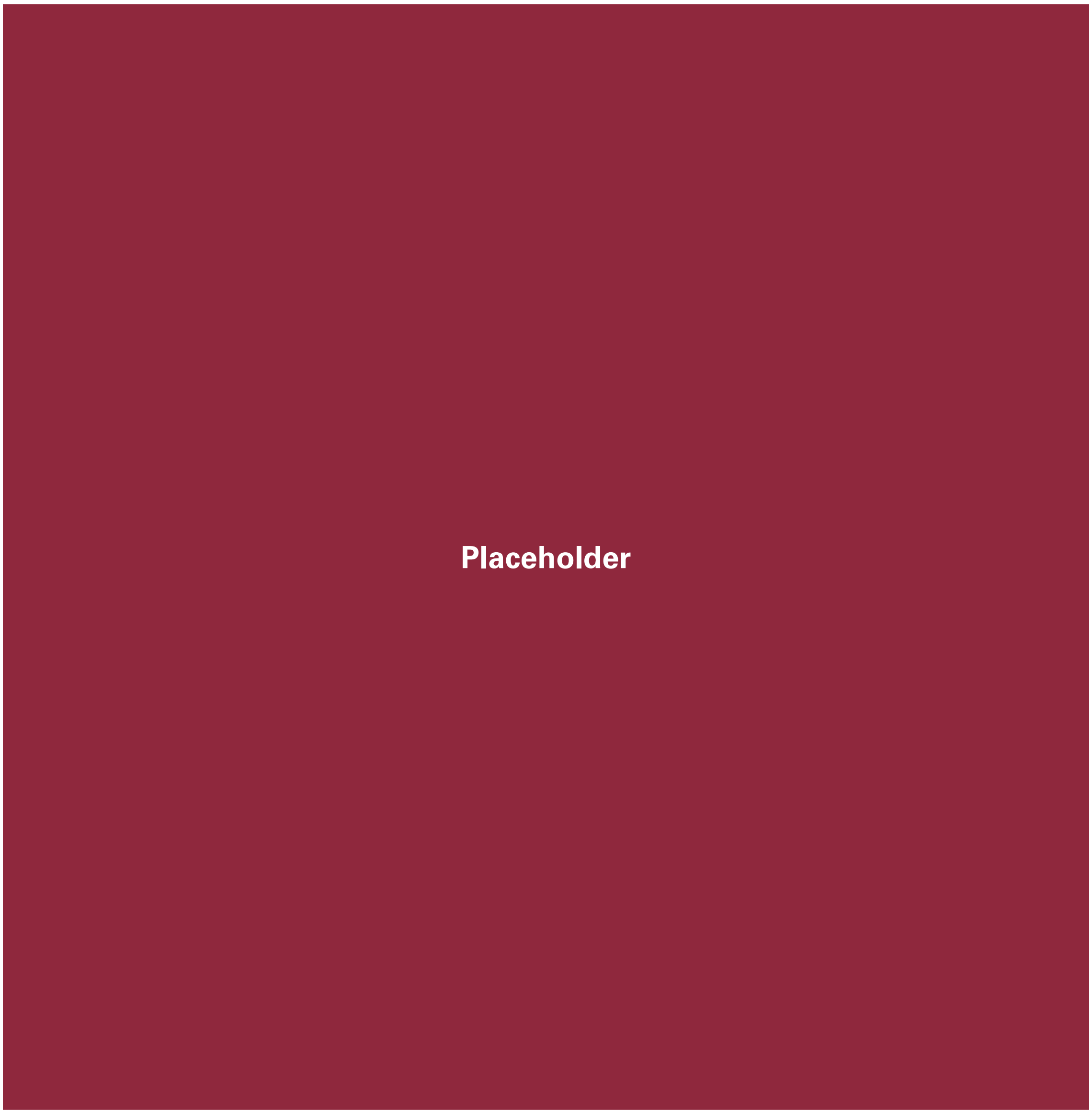

Figure 19: White Blood Cells (irregularly shaped leukocytes), are according to Capra (1996, p.277) "bits of the brain floating around in the body." This is due to the fact that they produce peptides that in simple terms are biochemically responsible for regulating mood and emotions. This effectively means that rather than emanating only from the brain, emotions colour "all sensory perceptions, all thoughts, and, in fact, all bodily functions" as the nervous system and various other organs are all lined with or are affected by peptides. The interiority of the body is therefore inextricably linked to the brain and perception, illustrating the case for a distributed mind that goes beyond the centrality of the brain.

1.8.7. Vital Materialism and Crystallisation

Lastly, there should be a further point of clarification in regards to vital materialism, which is one of the main strands of the new materialist discourse. Having been initially formulated and extensively discussed by Hans Driesch (Bennett, 2010; Capra, 1996) and Henri Bergson (1998; c1998), the contemporary take on the theory by Bennett (2010, p.13) maintains that: "all bodies are kin in the sense of inextricably enmeshed in a dense network of relations. And in a knotted world of vibrant matter, to harm one section of the web may very well be to harm oneself." This vitality can be extended to incorporate non-human bodies and in some cases excluding the involvement of the human mind[24]. In effect, the present thesis is not concerned with that specific discourse, nor does it investigate any life-like properties of matter or being. When arguing against the hylomorphic model by putting forward his theory of individuation, Gilbert Simondon (1989) discussed this firstly in the process of *crystallisation* and subsequently in *living being*. What follows will be concerned with the former, but also with the human parameter added to the agency of this crystallisation process.

1.8.8. Sub-Research Question 02

The corresponding theoretical sub research question therefore posed here is *how can the dualist relation between form and substance and the designer's engagement with materials be rethought through the proposed design workflow*.

1.9. Methodology

1.9.1. Overview

In terms of the methodology followed to answer and attain the objectives that have been outlined, this will consist of four main parts that are divided into an equivalent number of chapters and are namely, *2. Achieving Fusion- A CAD Literature Review and Fusion Design Studies*, *3. Designing Blends- The Epistemology of Blending Simulations and Main Computationally Blended Design*, *4. Thinking with Blends- A Conceptually Blended Design Methodology*, and *5. Visualising and Fabricating Fusion*. As it will be mentioned in the CAD literature review, due to the novelty of the subject of graded material design, a main limitation in the thesis has been that any precedents of historical value or any built examples, are *non-existent*. In addition, although there is information available that is published in the form of research papers and proceedings books, this is of a scientific nature and to a very large extent inaccessible by a non-scientific and non-specialised audience. Additionally, the design investigations that can be found in research and conference paper formats as well, are equally technical in nature. This is due to the fundamental problem that exists in graded information design currently, which relates to the main hindrance that is presented when one is even beginning to design with multi-materials in the computer[25]. This in effect, has resulted in any relevant design research being focused on coming up with customised CAD approaches to this problem and therefore eschewing a focus on design-theory.

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24 Bennett states that she is "in search of a materialism in which matter is an active principle and, though it inhabits us and our inventions, also acts as an *outside* or *alien power* [emphasis added]" (Coole and Frost, 2010, p.47).

25 Bearing in mind that all commercially available CAD software is non-materially biased.

Thus, and as it will be evident, the research in *2. Achieving Fusion* and *3. Designing Blends* becomes occasionally technical and quantitative in scope, but as mentioned, merely to the extent that it can initiate and sustain the design workflow proposed in the thesis, as well as in order to validate some of the assumptions that otherwise have no precedent and body of similar work to compare to. Once this workflow is established, *4. Thinking with Blends* consists of an examination and interrogation of the design methodology from a theoretical perspective and in regards to the cognitive and mental processes involved.

Furthermore, chapters 2 and 3 are presented in a sequential order from first to second, but they could very well be changed in sequence or weaved together to make the point that the process proposed should not be seen as comprised of compartments or stages that are introvert and with rigidly defined boundaries. Rather they should be perceived in terms of their aforementioned *interiorities* i.e. parts of the contents of each stage, being able to "mix or mingle" (Ingold, 2015, p.22), and blend together, become reversed in order or performed in an alternative sequence. All this will be evidently much clearer later in the thesis.

1.9.2. Methodology Outline

The methodological analysis that will follow will in effect be structured as follows:

a. Research about appropriate materials to be used in the multi-material design and on existing techniques for manufacturing these materials.
b. Setting out of a material simulation with the objective of the parameters in the simulation resembling physical parameters as closely as possible.
c. Design of curtain wall detail through the material fusion simulation.
d. Use of conceptual blending and material engagement theory in the design process to demonstrate the inseparability of mental processes, form and material.
e. Visualisation and fabrication of the designed multi-material.

1.9.3. Achieving Fusion Outline

Looking into the chapters individually, *2. Achieving Fusion* will be focused initially on providing a literature review of the current research initiatives taking place in multi-material design, as well as on briefly discussing the CAD tools used in the process. Following that, there will be an extensive review of the software that can incorporate graded materiality, as well as its critique and corresponding selection of an appropriate technique that will be employed in response. The series of studies that will then follow will be focused on achieving material fusion in the computer using the technique that was identified. Each of these will conclude with a brief analysis of the results and critique of the shortfalls of the operation.

1.9.4. Designing Blends Outline

3. Designing Blends, will consist of a design study that is a pre-amble to the main design and in which the epistemological parameters relating to the use of simulations as a design tool will be discussed. The main endeavour there will be to demonstrate the validity of using a graded material, present the benefits that this has on a quantitative level, and at the same time discuss the central subject of the chapter, namely the degree of adherence to reality that ought to be attained in a simulation. This will be carried through into the design of the curtain wall interface and together with research on functionally graded materials in nature, identification of appropriate sub-materials to be used in the larger multi-material entity, and structural analyses on a typical curtain wall panel it will form the framework for setting out the design simulation.

1.9.5. Thinking with Blends Outline

In *4. Thinking with Blends*, there will be a brief history presented of the ubiquitous CAD design element of today, its physical origins, computational assimilation, and eventual correspondence to a material-less, formal approach to design. This will be followed by a presentation of Conceptual Blending Theory and the main constituents of it, followed by the application of the theory in the design process and in order to demonstrate the conceptually blended manner that the design operations take place in. Additionally, in the latter part of the chapter, references from abstract and live art will be used to discuss the problem of agency in the process, effectively leading into a prognostication about the gradual indiscernibility between form and substance through the use of computational design interfaces of increasingly advancing sophistication.

1.9.6. Visualising and Fabricating Fusion Outline

In *5. Visualising and Fabricating Fusion*, the emphasis will be on the way that the design that was generated in *3. Designing Blends* can be visualised, as from what it will be evident this is not such a straight-forward process as the one performed conventionally. Material anchoring, an extension of Conceptual Blending theory, as postulated by Hutchins (2005), will also be employed in the process in order to elucidate the mental processes occurring during the visualisation workflow. Additionally, the focus in the fabrication subchapter will be primarily with translating the digitally generated gradients into ones that are physical, with a parallel conversation revolving around the convergence and immediacy between design and fabrication.

1.9.7. Conclusion Outline

Lastly, the conclusion will consist of an analysis of the main and secondary contributions of thesis, as well as a discussion about the potential mutability of the FGM design workflow that forms the main output of this research. Additionally, there will be a discussion of the methods for evaluating the main theoretical arguments and design artefacts of the PhD, a presentation of the value of the research and potential areas for further investigation, and lastly an envisaged 'roadmap' of multi-material integration in architecture.

02

ACHIEVING FUSION

2.1. Literature Review

Looking into the application of FGM in architectural design, one of the initial problems is the aforementioned lack of available precedents that can inform the design process. Information exists in a format that is addressed to specialised audiences and typically consists of scientific terminology that is to a very large degree incomprehensible and therefore inaccessible by architects. On the other hand, one can find publications in fields that are peripheral to architecture, such as material science, that contain a substantial amount of information but of a technical nature. At the same time, the vast majority of this research is of an analytical scope, focusing mainly on the properties of FGM, the methods that they can be manufactured with, as well as how the different methods can affect their morphological, bonding and density characteristics (Yu et al., 2007; El-Hadad et al., 2010; Watanabe et al., 2009; Mahboob et al., 2008). Additionally, as opposed to established research areas, such as the broader field of generative design, in which there already exists a substantial body of work, the nascent area of multi-material design is only beginning to come into existence through a limited number of scattered research initiatives that vary greatly in their focus. Furthermore, there is lack of a comprehensive design theory or criteria through which it would be possible to critique and evaluate any relevant design projects.

2.1.1. Existing Graded Material Design Research

In terms of the design research initiatives, these are currently taking place in academic institutions in Europe and the US and are to their clear majority restricted to either speculative endeavours or small to medium scale-build research. This is mainly the case due to the high costs involved and the fact that multi-material additive manufacturing is still in its early stages of development (albeit advancing very rapidly). Designers that have conducted or are conducting studies in this area at present are Rachel Armstrong at the University of Newcastle (Grigoriadis, 2016), Tom Wiscombe (Spina and Gow, 2012; Wiscombe 2012; 2010) at the Southern California Institute of Architecture in Los Angeles, Neri Oxman and Alexandros Tsamis (Grigoriadis, 2016; Tsamis, 2012; 2010) at the Massachusetts Institute of Technology in Boston, and more recently Daniel Richards and Martyn Amos (Blaney, et al., 2016; Grigoriadis, 2016; Richards and Amos, 2014) in the UK and Panagiotis Michalatos and Andrew Payne (Figure 20) (Michalatos, 2016; Grigoriadis, 2016; Michalatos and Payne, 2013) in the US[26]. The different media and themes explored under the umbrella of gradient materiality are ranging from structural and mechanical

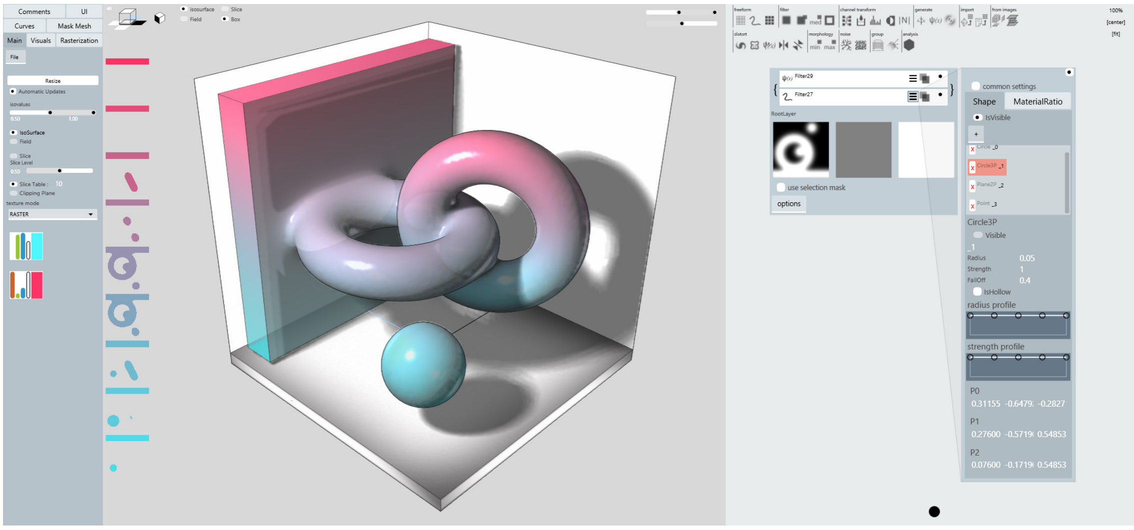

Figure 20: Screenshot of Monolith, the voxel-based software created by Michalatos and Payne. Essentially being a three dimensional version of Photoshop, multi-materials can be applied in the program as colour gradients on 3D volumes, using functions, bitmap mapping, and free painting among other operations.

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26 Another researcher that ought to be mentioned is Skylar Tibbits (2016) based at the MIT Self-Assembly Lab, whose work often refers to or deals with multi-materials as well. These, however, are approached as layers of two or more materials, akin to laminates, and with the objective of harnessing their differing properties in order to enable self-assembly. The focus is therefore different to the one of material fusion and gradients that is being investigated in the thesis.

building system convergence, gradient elasticity, rigidity and opacity to the creation of novel variable material property design workflows, as well as variable material property fabrication systems. In terms of the computational techniques employed by the above designers for working with graded information, research has shown that this is solely restricted to utilizing voxels (Figure 21) (Grigoriadis, 2016; Bader et al., 2016; Doubrovski et al., 2014; Richards and Amos, 2014; Michalatos 2016; Michalatos and Payne, 2013; Oxman, 2012b; 2011a; 2011b; Tsamis, 2012; 2010), a digital design technique that will be analysed and critiqued[27] in 2.2.5.1. Indicatively, the proposed workflow will be departing from the use of voxels as the sole multi-material design method and will be utilizing fluid simulations to compute material fusion in its liquid form.

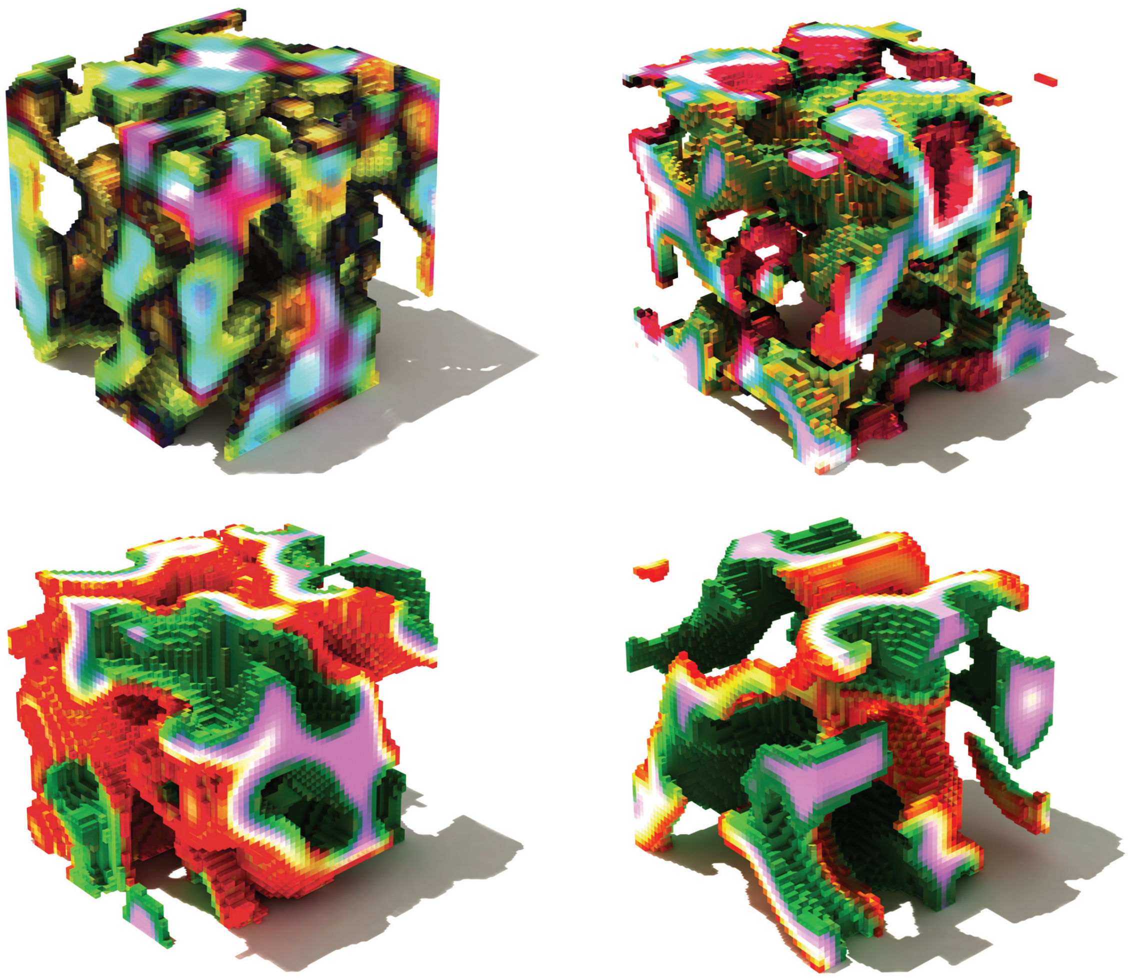

Figure 21: Voxel Variations of Property Shapes by Alexandros Tsamis. The variations are made in a custom made voxel-based software termed *VSpace*.

2.1.2. Existing Building Scale Graded Material Research

In terms of other research on larger scales or on the level of building componentry, this has been performed to a limited extent by Oxman, Keating and Tsai (2011) at MIT that were investi-

27 Due to their inability to incorporate material properties in their data structure.

gating the possibilities of fabricating variable property concrete components[28], and more extensively in the field of engineering by Michael Herrmann, Pascal Heinz and Werner Sobek at the Institute for Lightweight Structures and Conceptual Design at the University of Stuttgart[29] (Figure 22). Published as part of the *Zukunft Bau* research initiative by the German Federal Ministry of Transport, Building and Urban Development (2011), the research undertaken at the Institute[30] consists of in-depth material testing investigations and structural analyses of variable material property building components such as beams and columns. Although having acquired funding from the German government towards further development of the technology (which comes to demonstrate the validity of the future use of graded material components in construction), this type of work is limited to a highly technical domain and does not incorporate any design-based investigations into the use of graded materials in architecture.

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28 Described in this research article are suggestive applications of material grading in the form of variable porosity concrete samples, as well as "variable-density fabrication" with silicone and ABS plastics. In this case, the term functionally graded is confined to "spatially varying composition or microstructure" (Oxman, 2012, p.93) of a singular material, the porosity and density of which are made to change according to structural loading criteria. The present research thesis, however, is investigating graded material design that adheres to the original definition of FGM that "integrate a variety of dissimilar materials and properties" (Shiota and Miyamoto, 1997, p.1).

29 The main works include investigations in *Manufacturing Methods and Fields of Use of Functionally Graded Structural Components in Construction Engineering*, *Functionally Graded Materials in Construction Engineering, Development of Weight-Optimised*, *Functionally Graded Precast Floors*, and *Graduated Building Components: Production Procedures and Areas of Use for Functionally Graduated Building Components in Construction* (Federal Institute for Research on Building, Urban Affairs and Spatial Development within the Federal Office for Building and Regional Planning, 2011).

30 Another piece of work produced at the Institute that should be mentioned, is the Engineering Doctorate dissertation titled *A New Connection Technique for Unidirectional Fibre Reinforced Plastics with Glass and Carbon Fibres* (OPUS, 2015). Its research subject is strikingly similar to the one presented here and concerns the rethinking of the connection of glass to its surrounding metallic frame in a building envelope. It is, however, approached purely as an engineering problem and effectively resolved through the introduction of fibre reinforcement (i.e. very much like a composite, as opposed to a multi-material) placed within and connecting the glass and metal parts.

Figure 22: A Functionally Graded Concrete Wall Sample, built at the Institute for Lightweight Structures and Conceptual Design at the University of Stuttgart by Michael Herrmann.

2.2. CAD Literature Review

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

Looking into the computational design techniques in more depth, overall, Computer Aided Design with gradient materials is something that does not exist in *commercial* CAD software used in architecture at present. Existing software packages represent volume and space through what is known as *b-reps* or *boundary-representation-objects*, which are essentially representations of the limits of a surface or volume within the digital environment. Complex forms are then constructed through cutting up and welding together individual b-rep parts that when joined together they generate complex and yet hollow representations of the equivalent of envelopes (Figure 23). Eventually, the way that digital constructs of representations of buildings or building parts are made, is through accumulations of these discrete elements or b-reps that are stacked together like a kit of parts to create larger three-dimensional assemblies.

Figure 23: Screen-shot of B-Rep Elements. 3D modelling software typically employ points, curves, surfaces, and meshes to generate three dimensional volumes, eschewing the incorporation of materiality.

2.2.2. CAD Limitations

Thus, "describing the material composition of the enclosed volume at any point is not possible with current CAD systems" (Knoppers, et al., 2005, p.469). In a more recent article Oxman (2012c, p.263) states that:

> "neither computer-aided design (CAD) tools nor industrial fabrication processes are [...] set up to represent graduation and variation of properties within solids such as varied density in steel or varied translucency in glass. As a result, the design process is constrained to the assignment of discrete and homogeneous material properties to a given shape."

2.2.3. CAD Limitations- Potential Workarounds

2.2.3.1. Rendering Software

One of the workarounds towards representing graded materials is by utilising rendering software through which, texture, bump and image maps can be mapped onto b-rep objects in order to give an impression of colour or texture gradients. This is done by loading jpeg images of gradients on the diffuse layers of materials within the program and then using surface, planar, box, spherical etc. mapping in order to wrap and stretch the loaded images on the geometry of the target surface. The use of this technique, however, is merely for visualization purposes and due to the nature of the CAD software only limited to application in b-reps, as well as not dealing of course with three-dimensional material depth or with material properties.

2.2.3.2. Customised CAD Tools

In this respect, there are two potential routes in terms of pursuing an appropriate digital design methodology. The first one is to follow a directly technical approach where the practical aspect of the research is focused on designing a basic digital tool that would enable the assigning of variable material properties. This approach has already been researched into by Knoppers, et al. (2005, p.470) through their "TNO software program Innerspace™," and by Oxman (2011a, p.27) with a novel software environment termed "Variable Property Modeling (VPM)", which according to the author is essentially a software package with form-finding capabilities informed by heterogeneous material distribution. In addition, Tsamis (2012) has devised VSpace (Figure 24), which is a "computer drawing application for designers. Unlike traditional CAD systems that work primarily by representing boundaries (B-rep), VSpace derives form by the representation and direct manipulation of properties (P-reps) in space." The main argument that Oxman (2011a) and Knoppers et al. (2005) make in favour of creating a new software environment is that the existing graded information tools have limited capabilities that stem from the very large amount of computer memory and processing power that is required to perform complex tasks. Moreover, they claim that the editing of any entities within these environments is problematic.

Responding to this, and in regards to TNO that is custom made to deal with material heterogeneity, the software operates by importing geometries within the relevant CAD environment and by using the interface of the program to assign multiple materials. The user effectively assigns material properties at specific instantiating points on the volume of a solid in an arbitrary manner, with the properties at any other point on the solid defined in relation to these initial locations. The objective of using this piece of software is to prepare CAD models for multi-material 3D printing, while when utilised in other fields such as engineering this type of top-down graded materiality assigning is within discrete industrial and automotive parts, and is targeted to areas that is known that they will be exposed to very high temperatures and will therefore require the use of a functionally graded material. In regards to VPM and VSpace, these are both voxel-based and the use of them will be argued against in 2.2.5.1.

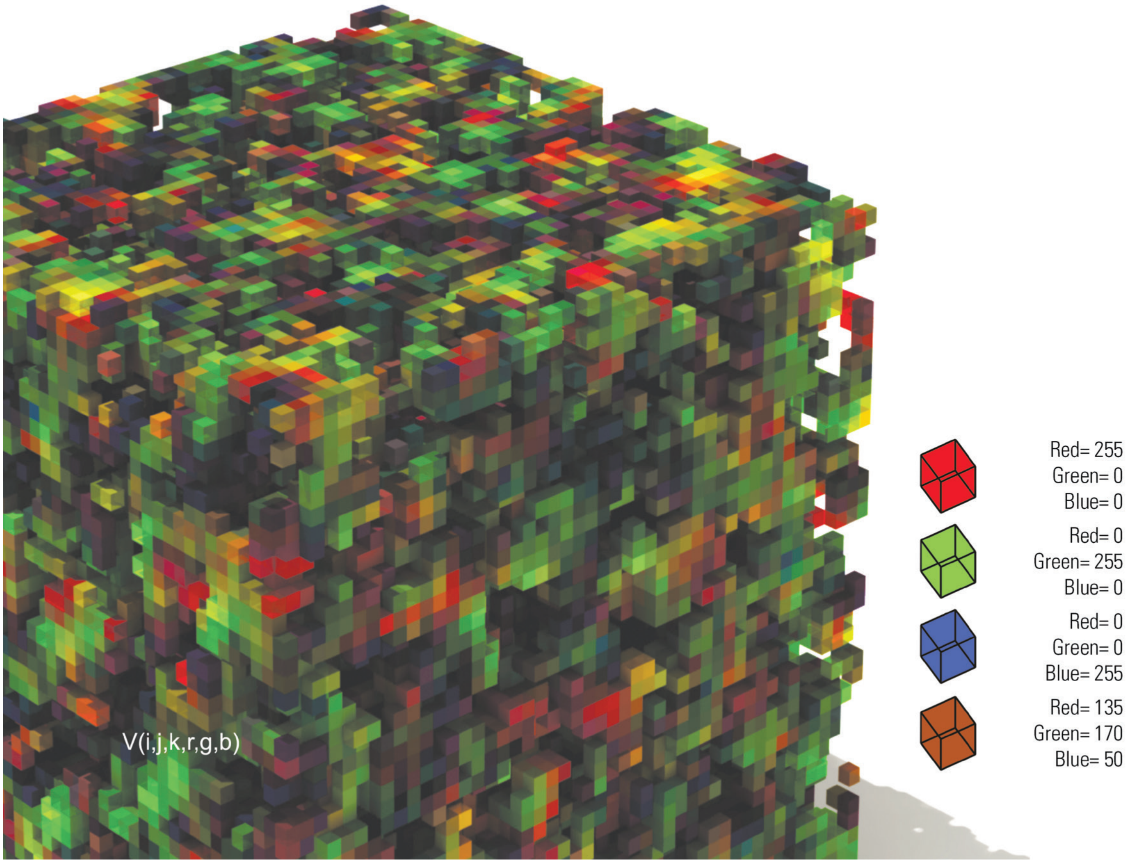

Figure 24: VSpace Voxel Arrangement. According to Tsamis (Grigoriadis, 2016, p.56) "for VSpace voxels are not considered bricks. They are primarily *information place holders*. They have a location in space V(I,j,k) relative to other voxels in the array and they hold information in the form of numerical values (properties A,B,…). Three properties A,B,C in VSpace are represented using color in the RGB space. In a generalized form a voxel is VSpace is represented as follows: V(i,j,k,r,g,b) with i,j,k = Z+ U {0} and 0 < r,g,b < 255."

2.2.3.3. Customised CAD Tools Critique

Effectively, taking the route of generating a customised software would have required a substantial part of the research to be dedicated to inter-disciplinary collaborations with computer science experts and to resolving the various technical and scientific parameters of such an attempt. This would have also meant that a much smaller amount of resources and effort would have been put into developing and framing the design and theory-driven investigation of the research subject. Moreover, (as it will be explained further in chapter 4.) the main objective is to rethink the standard b-rep oriented design workflow and the corresponding cognitive operations that go with it, therefore concentrating on software design would have contradicted this scope. This potential avenue of investigation has therefore been eschewed.

2.2.4. Existing Graded Information CAD Tools

The second route is to explore software that is used in other disciplines, adjacent to the field of architecture that can be accessible from a design-oriented perspective. Extensive research has shown that the only sources that provide a concise overview of the available computational techniques for designing with graded information are the research articles *The Reality of Functionally Graded Material Products and The Design of Graded Material Objects*, by Knoppers et al. (2005, 2006), as well as the remarkably similar (in terms of its literature review) paper titled *Variable Property Rapid Prototyping*, by Oxman (2011a). According to these authors, there are four main options of "mathematical models to describe FGM structures" (Knoppers et al., 2005, p.470). Namely these are Voxels, Finite Elements Method (FEM) elements, Particle System Elements and Vague Discrete Modeling (VDM) elements. Oxman and Knoppers, et al. go on to specify the characteristics of each one of these techniques, as well as the limitations that they pose.

2.2.4.1. Voxels

Voxels are volumetric data sets that are the three-dimensional equivalents of pixels used in digital images. "The geometric accuracy of a solid represented by a grid of voxels is determined by the number of voxels. When accuracy is required, the use of voxels requires vast volumes of data storage and processing. Consequently, voxels are not the ideal entity to design and edit graded information" (Knoppers, et al., 2005, p.470).

2.2.4.2. Finite Elements

The Finite Elements Method is mainly used in the broader mechanical engineering discipline to perform numerical analyses, as well as to visualize the manner in which structures bend, twist or deform in order to optimize the design of industrial parts. In addition to being inaccessible due to the high degree of scientific knowledge required to use this method, "it was suggested that FEM elements could be used to model spatially varying materials distributions within FGM objects, [however,] the modelling method is inefficient for highly graded structures, so expected memory requirements and data processing effort are large" (Knoppers, et al., 2006, p.40).

2.2.4.3. Particle System Elements

Regarding particle system elements, these are:

> "objects that have mass, position, and velocity, and respond to forces, but that have no spatial extent. Because they are simple, particles are by far the easiest objects to simulate. [...] Since the particle [sic] show no coherence and there [sic] positions within a certain volume can change, particle system elements do not satisfy the requirements for graded structure modelling." (Knoppers, et al., 2006, p.40) (Figure 25)

2.2.4.4. Vague Discrete Modelling

Lastly, "Vague Discrete Modelling (VDM) elements have been developed so that the shape of a product doesn't have to be completely defined. [...] This model is still under development, and

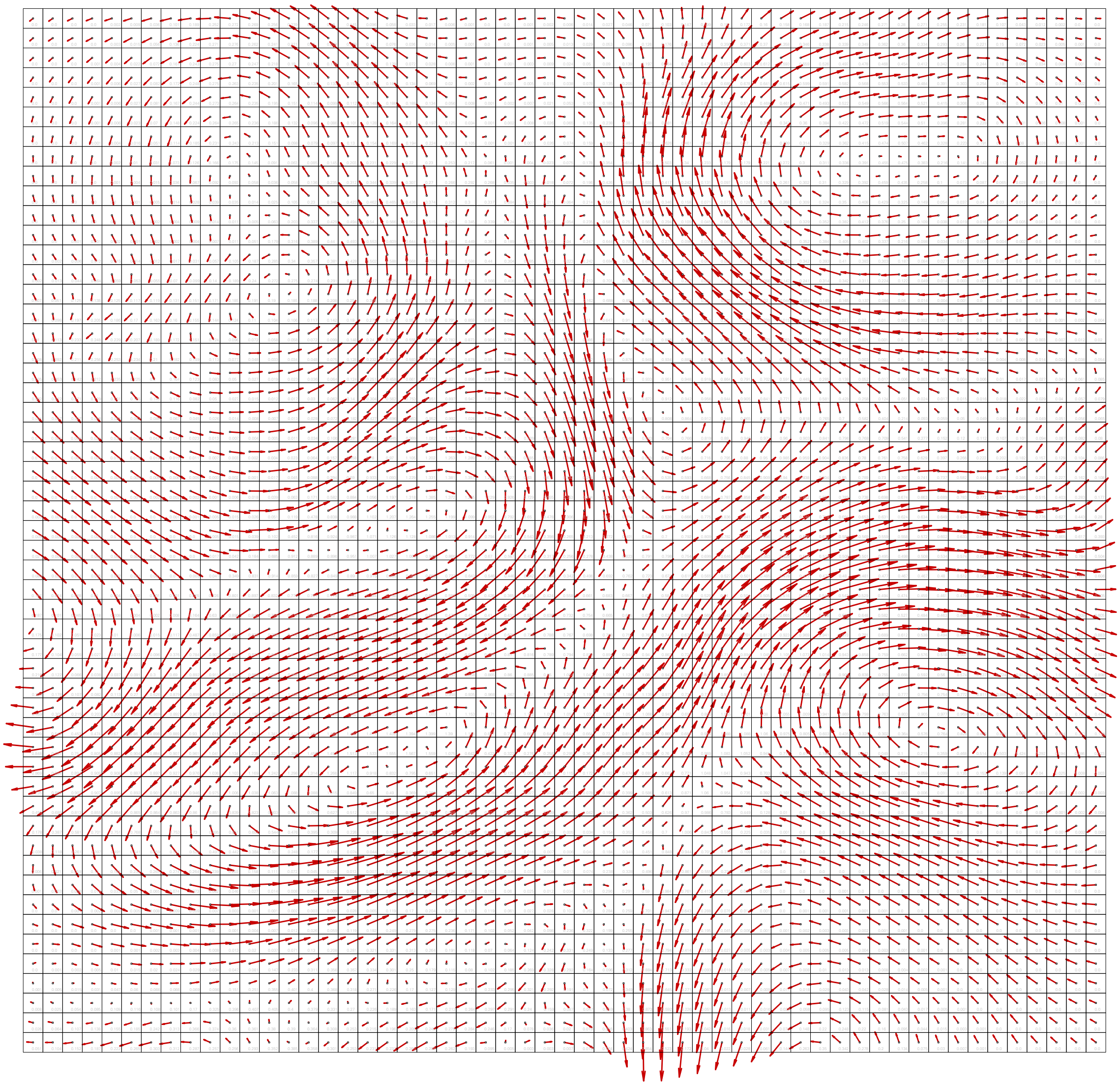

Figure25: Vector & Density Information Output from a Particle Simulation, created in Autodesk Maya. The underlying grid is generated in the software by default in order to discretize and compute the particle movement and behaviour at every spatial interval of the environment at each time-frame of the simulation.

particle definition doesn't meet the requirements to define graded structures" (Knoppers, et al., 2006, p.40).

2.2.5. Existing CAD Tools Critique

An initial response to this breakdown of potential tools is that apart from particle systems none of the above software take into account material behaviour which, when designing with materials being of equal importance to form, is of central value to the design process. More specifically, multi-material design is a process mainly concerned with the assigning of gradients between two or more dissimilar materials, as well as the extents of these. Being unable to attribute gradients based on criteria other than aesthetics, a designer ought to use simulations in order to allow for the gradients to be computationally calculated based on the physical properties of the substances to be fused.

2.2.5.1. Voxel Critique

More specifically, a criticism posed of the procedures that are voxel based (Grigoriadis, 2014) is that although they are to a certain extent highly sophisticated, at the same time actual material attributes are not taken into account. This critique can firstly relate to the fact that these platforms concentrate primarily on the distribution, positioning and assigning of materials in digital space, with a multi-materiality which nonetheless is of a representational nature as it is attributed as RGB colour values[31] and not as digitised physical properties such as density, viscosity, surface tension etc. Secondly, for the moment, the 3D printed parts that can be built with information generated from this software are similarly representational as the properties of the multi-material[32] that is 3D printed are not fed back and/or simulated into the digital environment. Thirdly, the compatibility between different substances and their chemical capability to bond in order to form a larger multi-material is another primary parameter that is not incorporated. All these can be summarised as the representation of materiality digitally, having as an output a 3D-printed representation of this representational materiality.

In this respect, this thesis argues against the voxel-based static model of prescribed representational material distribution, whether this is arbitrarily assigned or coming from specific scientific analyses of stress areas, loads etc. that can then hypothetically inform the manner in which gradients should be assigned. Arguing against this method is mainly because there is a fundamental difference between assigning material gradients in already designed tectonic parts or as a three-dimensional colour painting operation (which is what voxels essentially are), as opposed to designing directly with material gradients.

2.2.6. The Case for Particle System Elements

Effectively reverting to the use of simulations, the direction of the thesis will be in contrast to the aforementioned dismissing of particle systems as having no fixed state, constantly changing and being unable to develop coherent relationships between them. According to DeLanda (2011), it is the point with every dynamic system that there are instances in the evolution or playing-out of the system in time where a certain state of equilibrium is reached. Additionally, the classical view of physics holds that order is associated to a state of equilibrium. To the contrary, according to the science of complexity "we learn that non-equilibrium is a source of order. The turbulent flows of water and air, while appearing chaotic, are really highly organised, exhibit-

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31 Other values that can be incorporated are surface normal vector information, opacity, and volumetric flow rates.

32 Limited solely to plastics at the moment, but at the same time indicating the exponential development of the technology, Objet, the company that patented multi-material printing had the technology to 3D print one hundred and seven different plastics in 2012, which three years later became one hundred and forty.

ing complex patterns of vortices dividing and subdividing again and again at smaller and smaller scales" (Capra, 1996, p.184). As it will also be explained later on, when playing out a material fusion simulation there is a certain point in time that a specific type of gradient (the characteristics of which are described in detail in 4.3.7.10.) will be formed that puts in place a very specific piece of criteria that signifies when the simulation should be stopped. Prior to this, the materials to be fused have not yet formed adequate bonding and dissipated enough into one another, while following that specific point in time, the substances will start getting dissolved into each other, with the resulting mix resembling an alloy, as opposed to a functionally graded material.

2.2.7. Design Tool Use Originality

This is something that effectively cancels out the first argument by Knoppers et al. (2005) of particle system elements perpetually altering their state and no coherent patterns being formed between them. Effectively, and as opposed to the aforementioned object-oriented approach, this technique will offer the potential for a generative assigning of material gradients, where the parameter of time allows these models to evolve sequentially and with material distribution finding its own fitness and arrangement in space. In terms of this specific design methodology, it is where *part of the originality of this thesis is based*, since *the use of widely available computational fluid dynamics simulation software to directly design materially graded architectural elements is something that has not yet been researched into on a doctoral level in architecture*.

2.2.8. The Case Against the Dismissal of Particle System Elements

The second argument that Oxman (2011a) and Knoppers et al. (2005) formulate, in regards to the large computational processing demands that particle system elements require, using a standard desktop computer with an Intel(R) Core(TM) i5-2400S CPU @ 2.50GHz 2.50GHz processor, installed memory of 16.0 GB, and a 64-bit Operating System, x64-based processor, to simulate the fusion of at times six materials in total, has posed no problems whatsoever on the computational capability required to perform the task.

2.2.9. Appropriate CAD Tool Identification

With all this in mind, the scope of the practical part of the research will be to reinstate and explore particle systems as a valid technique for generating fields of discrete, interacting, information-loaded point fields that can be manipulated to gradually alter their arrangement. Furthermore, as they are by virtue of their computational structure made to simulate natural phenomena and effectively the behaviour of materials in their malleable state, they will be used to simulate the graded fusion of materials in the glazing to frame connection presented hereinafter.

03
DESIGNING BLENDS

3.1. Pre- Blends

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

For the purpose of the design studies that follow, the approach has been to strip down the theoretical scope of the research to its bare minimum, and at this stage only focus on achieving the gradient integration of two materials digitally. This simplification has been deemed necessary in order to firstly identify appropriate software (out of a range of commercially available particle system element packages) that can be used to realise this fusion, with the idea then being to progressively escalate the design complexity of the study, and follow this up with a theoretical analysis of the design process. Furthermore, apart from the formation of gradients, design studies 01 to 05 will be concerned with the attribution of properties that are *intrinsic* to the materials. Following these, design study 06, as well as the main curtain wall interface design will be concerned with the attribution of parameters that affect the behaviour of fluids in the simulation environment and are extrinsic to the fluids themselves.

In effect, the starting point here has been to use fluid dynamics particle software to generate gradients, which in the cases that follow were in the form of colour gradients.

3.1.2. Design Study 01

A first exercise was set in the 3D graphics software *Maya* utilizing the in-built engine for generating effects that "behave according to the natural laws of fluid dynamics, a branch of physics that uses mathematical equations to calculate how things flow. [To generate these] dynamic fluid effects, Maya simulates fluid motion by solving the Navier-Stokes fluid dynamics equations at each time step" (Autodesk Maya 2013 Online Docs, 2013).

3.1.2.1. Controllable Parameters

As fluid emitters in the program must be placed inside a container within the volume of which the simulation will eventually take place, a default two-dimensional square container of ten by ten units formed the bounding domain for the initial study. The fluid behaviour itself can be controlled by a quite diverse set of *intrinsic* parameters that include viscosity, friction, damp, buoyancy, dissipation, diffusion, tension and tension force to name but a few, that can all be recursively adjusted towards achieving a desired effect. Indicatively, running a simulation in default mode over the standard timespan in the software with only one emitter at the centre of the container, typically results in the fluid being emitted upwards and becoming concentrated in the upper part of the container (Figure 27).

3.1.2.2. Simulation 01

The next step in this study was to use the internal to the fluid self-attraction and self-repulsion parameters, in order to achieve the formation of gradients in the arrangement of the fluid in virtual space. After iteratively adjusting these inputs it was observed that keeping the values of self-attraction negative and between -1.0 to 0.0, the simulation would start off with the fluid trying to preserve its radial coherence as much as possible and building up in density within the same circular area. After a few timeframes, this internal coherence would break up at four opposite points of the starting formation resulting in the fluid being released from these points diagonally across and forming an X-pattern that would exhibit a vortex-like movement within the container space. As there was an incandescent value added in the parameters, the building up of fluid would mean that it would change colour becoming more yellow (from red initially) in the areas of higher density (Figure 28).

3.1.2.3. Simulation 01- Critique

In terms of evaluating the output of this initial simulation, and as the objective of the practical part of the research at this stage was to generate computational gradients, the degree of success of the exercise was directly linked to the degree of colour gradient formation in the fluid.

Due to the fact that a two-dimensional container was utilised and because of the input self-attraction, repulsion and incandescence values, the flat arrangement of the fluid at any given time-frame would exhibit areas of higher or lower density of fluid build-up. There were areas where this concentration would be of an intense yellow colour and other places where the fluid would be sparser having a dark red colour hue, with these opposing conditions, however, gradually fusing into one another and generating gradient colour fields.

3.1.2.4. Simulation 02 & Design Study 01 Critique

The same exercise was repeated with two emitters of different colours this time, and by increasing the negative self-attraction values a similar output was attained (Figure 26). A closer evaluation of this study, however, showed that even though gradient formation was achieved, it was not possible to accurately simulate material behaviour using scientific values, mainly because the specific software is typically used for graphics applications and animations in the movie industry and effectively to serve visualisation purposes. The standard workflow followed in that context is through a process of trial and error, where a liquid flow for instance is simulated iteratively and the aforementioned parameters adjusted intuitively in order to achieve the correct results, based on visual criteria. What this implies in consequence is that although the

Figure 26: Snapshot of a Two-Emmiter Fluid Simulation, generated in Autodesk Maya.

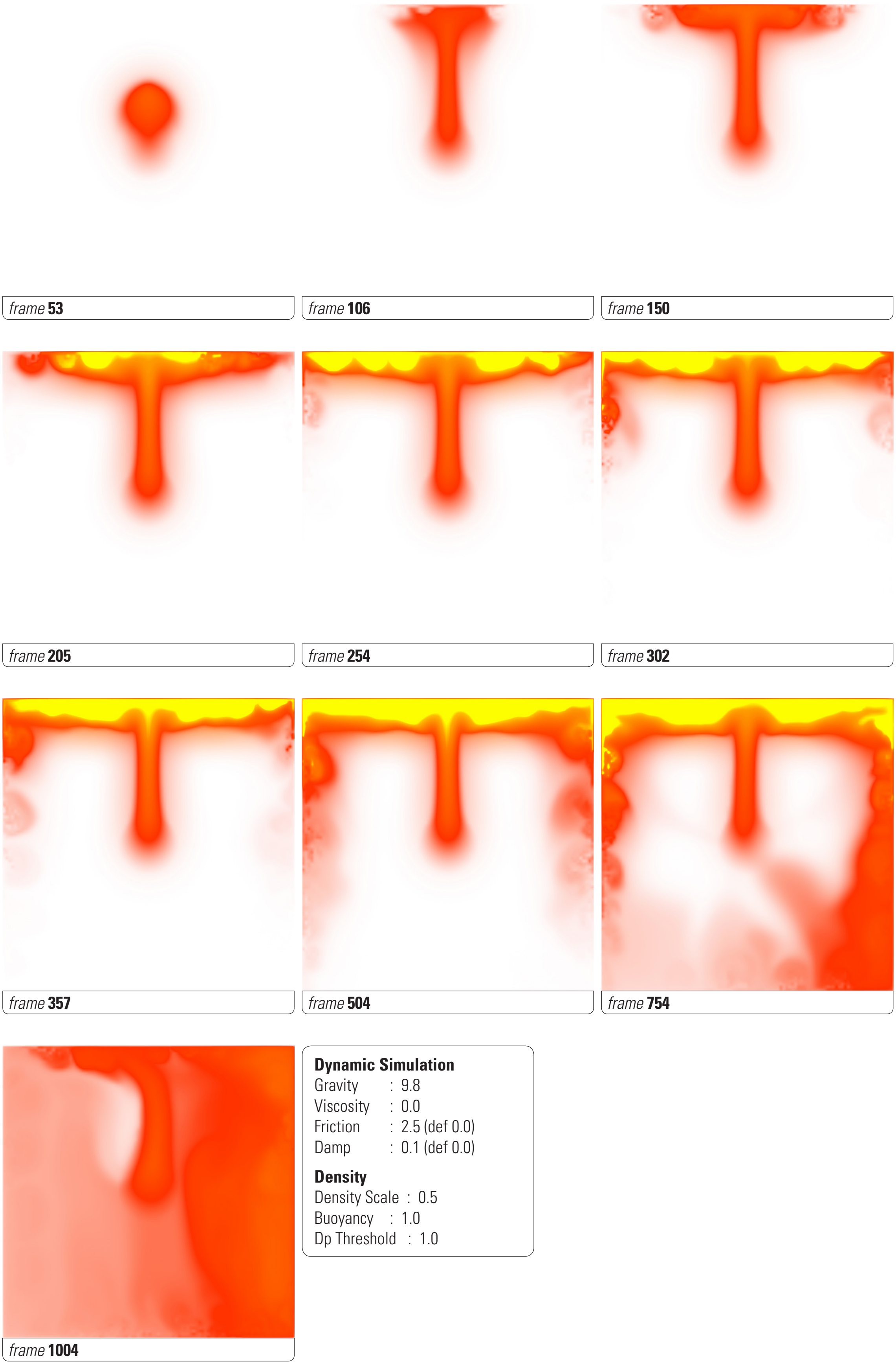

Figure 27: One-Emmiter Fluid Simulation with Default Values, generated in Autodesk Maya.

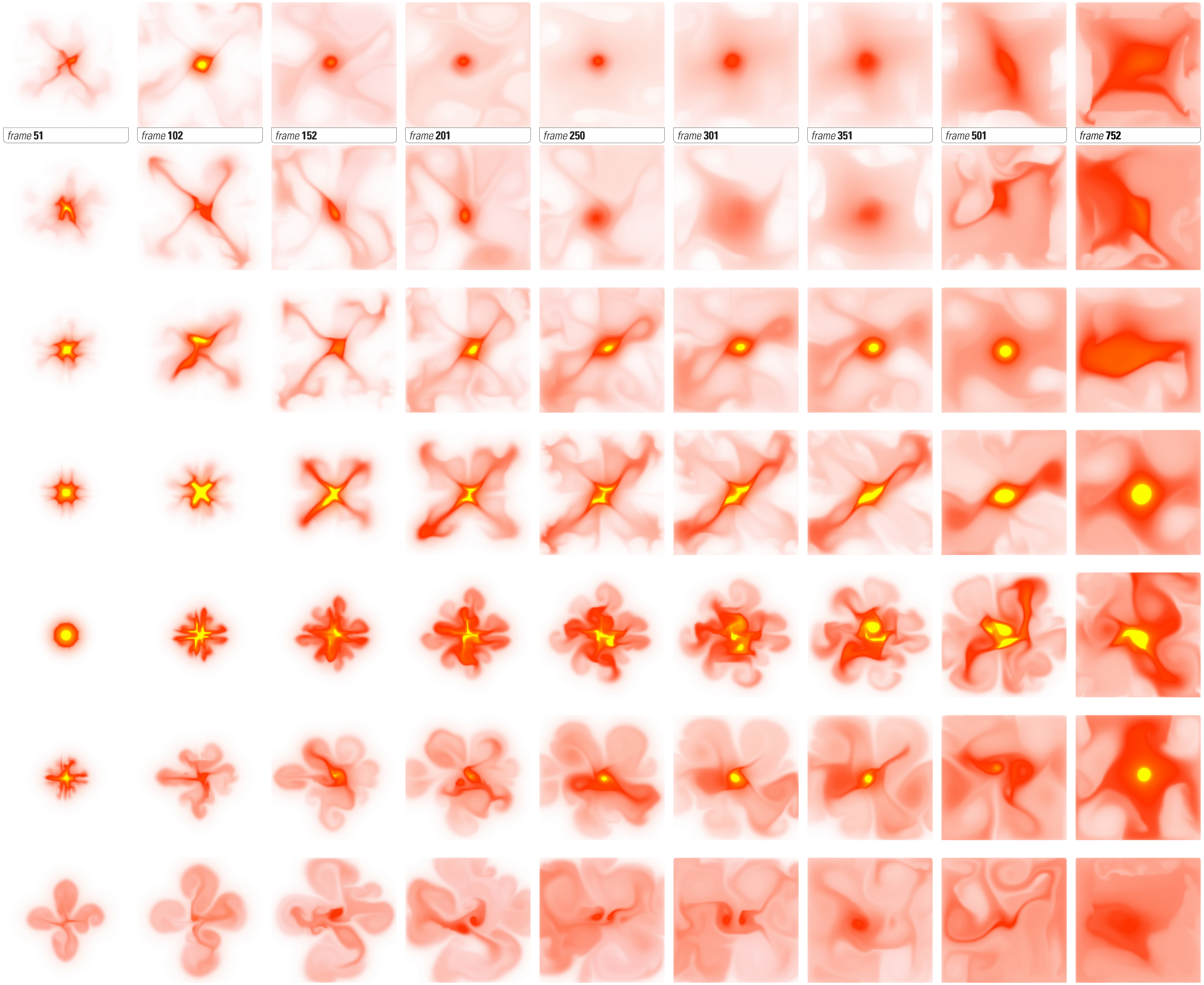

Figure 28: One Emitter Fluid Simulations, showing different arrangement attained under a variety of self attraction and repulsion settings. The objective was to achieve the formation of gradients.

effect of blending fluids together and creating colour gradients can be easily achieved, as it was the case here this is on an abstract level, with the emitted substances not being precisely attributed and correctly simulated liquid materials. Furthermore, one could assume that should actual material properties be incorporated in the simulation and having taken into account the physical correspondence and chemical reaction of one material to another, the resulting formations would most likely be altogether different.

A further limitation of this specific digital tool was that within a given simulation, two or more emitters cannot have different input parameters, as these values are applied to the emitter container overall and then automatically assigned to all included emitters. This effectively means that it is not possible to simulate the fusion of two fluids with different material properties.

3.1.3. Design Study 02

The second approach regarding the research into material blending in digital form was to use a software package in which individual material properties can be attributed more precisely. The software RealFlow, which is "ground-breaking in that it is particle based" (Kirkegaard, Hougaard and Stærdahl, 2008, p.9), was deemed suitable for attaining more realistic simulations. This is because "the elements of the simulation use physical properties to control their behaviour and can interact with each other and react according to impulses, forces and accelerations" (Kirkegaard, Hougaard and Stærdahl, 2008, p.9).

3.1.3.1. Controllable Parameters

The two main parameters that can be controlled through the interface of the program are the properties of the particles to be emitted[33], as well as the properties of the mesh that is typically employed to generate "a three-dimensional representation of the outmost particles of one or more emitters. [In essence,] the mesh engine puts a sort of skin over these particles to visualize the fluid's volume" (RealFlow 2015 Documentation, 2015).

3.1.3.2. Controllable Parameters Evaluation

In terms of the particles, the inputs that can be adjusted in the particle system are density, internal and external pressure, viscosity and surface tension. Examining these more closely, however, and following a first set of tests in which a volume of water was dropped on another body of water partially filling a rectangular container, it was realized that although some of these inputs are standard scientific units (with density for instance measured in kilograms per cubic meter) other input parameters are not *physical properties* but *physical values*. In addition, "there is no hard rule on selecting these values; it depends on the look the users want as well as

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33 These properties are essentially the aforementioned *intrinsic* material properties.

scene scale and the forces being applied. How the user knows what value to set depends to a large extent on experimental trials, experience, and also knowledge of the physics" (Kirkegaard, Hougaard and Stærdahl, 2008, p.10). It was evident therefore, that the tool can be partially controlled in terms of its accuracy, with a more complete degree of attained precision stemming from the aforementioned trial and error process, as well as observation skills of the user.

3.1.4. Design Study 03

A further study was effectively set up, in order to test out the above observations through the mixing of two liquid materials, namely oil and water (Figure 29). The aim of this exercise was to assign all possible parameters as direct properties, while the remaining ones (i.e. values that do not receive precise and scientifically measurable inputs) were assigned *relationally*, as well as through observing the behaviour of these fluids in physical reality. In terms of the *properties*, water has a density of 1,000 kg/m³ and oil 885 kg/m³. In terms of the *values*, although these were not directly scientific they were, however, relative to one another. Water for instance has a dynamic viscosity at 20 degrees centigrade of 0.00100 Pa·s (Pascal Second) and hydraulic oil (HLP 68) of 0.195 Pa·s (RealFlow 2014 Documentation, 2014), which would effectively mean that although scientifically measured assignment of these is not possible, the two fluids would have an approximate ratio of 1 to 195 in the viscosity parameter of the particle simulation interface. In addition, the same calculation can be done for their surface tension parameters as well, i.e. water has a surface tension at 20 degrees centigrade of 72.8 dyn/cm and oil of 31.0 dyn/cm, which equates to an approximate 2.34 to 1 ratio.

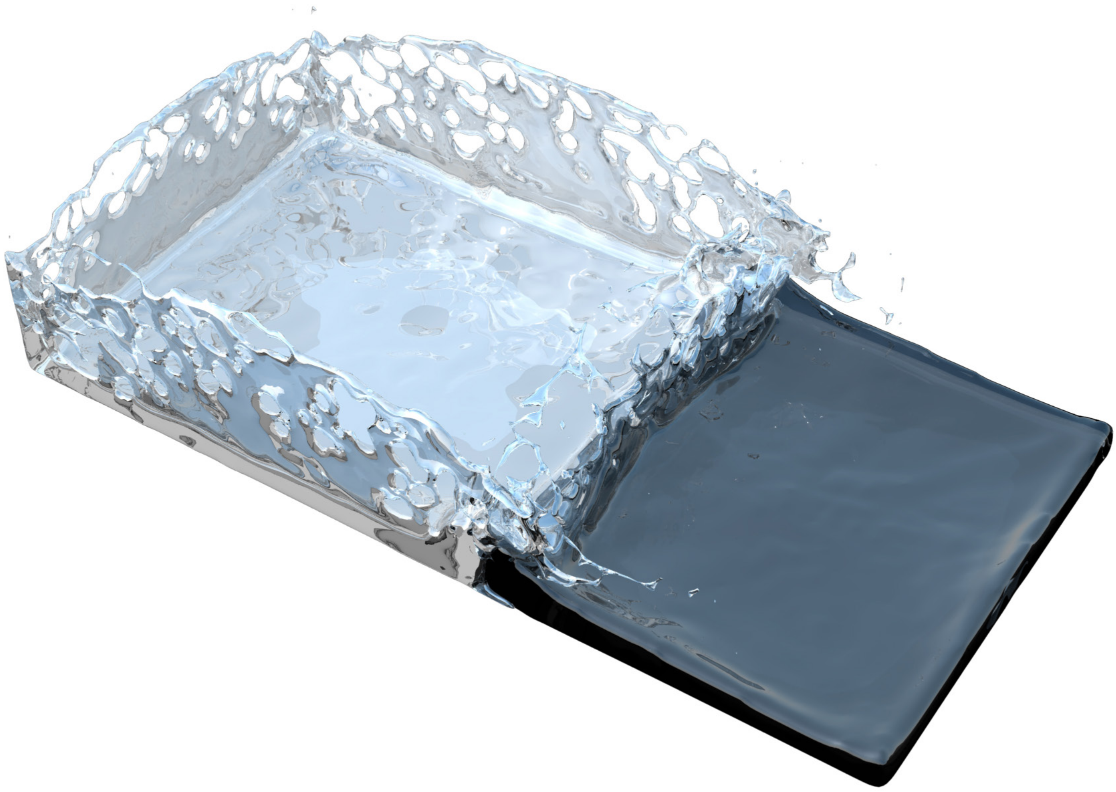

Figure 29: Snapshot of the Oil and Water Mixing Simulation, at the thirtieth second of the time span (for the full simulation see Appendix A).

3.1.4.1. Mechanism Independence in Simulations

Regarding this condition of the partially accurate simulation model, when DeLanda (2011, p.13) discusses the emergent qualities of simulations, he observes that "despite [their] differences a convection cell [(Figure 30)] and a chemical clock[34], as these reactions are called, are qualitatively the same. This implies that a full explanation of these emergent entities must possess a component that is independent of any particular mechanism".

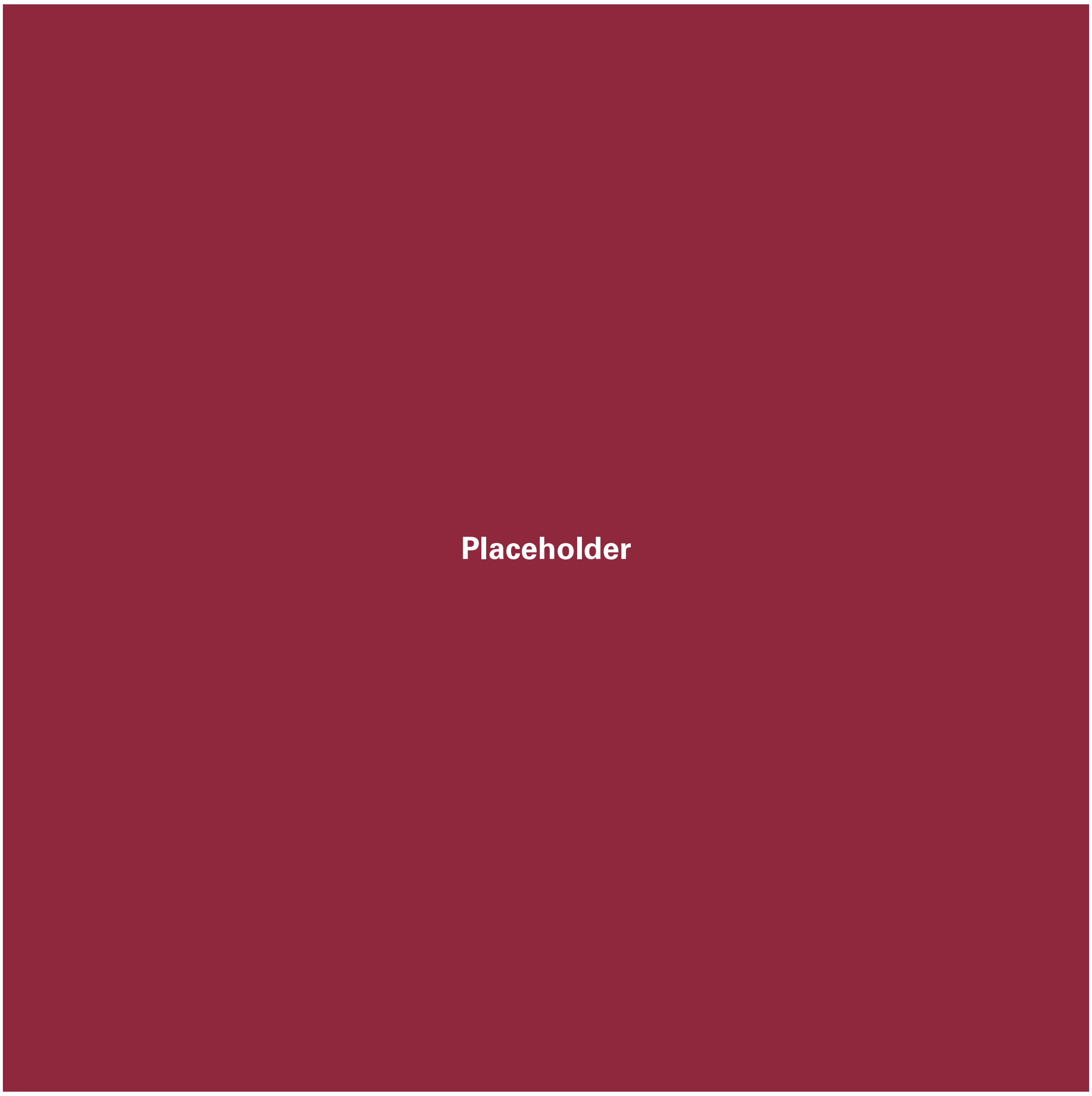

Figure 30: Cumulus clouds formed as a result of convective activity. Convection occurs when a fluid exhibits different densities within its volume. This takes place for instance when a body of water is heated up centrally from below and the heated region expands, becoming less dense and more buoyant. This causes it to rise to the top and the surrounding cold water to move to the bottom. The ascending liquid body is called a convection cell.

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34 In simple terms, a chemical clock occurs when the mixing of chemical compounds exhibits a non-linear periodic oscillation in the reaction taking place between the different substances. According to DeLanda (2011) this phenomenon is the same as a convection cell, as they both exhibit a rhythmic pattern of change.

What is described in this case is that for emergent properties to be studied one needs to set out a simulation model only partially, i.e. when dealing with temperature in a body of water, the temperature parameter can be taken as a granted value, omitting the kinetic energy and behaviour of the molecules that generate this specific temperature.

> "But once we add the mechanism-independent component the concept of emergence leads to two important epistemological consequences: it explains why we can use partial models to learn about reality and it provides an account for the capacity of those models to mimic the behaviour of the processes they model… When the emergent properties of a whole are stable they can survive changes in the details of the interactions between its parts." (DeLanda, 2011, p.13)

3.1.4.2. Partial Accuracy

Of course, here, the qualitative aspect of the emergence described is referring to scientific simulations of highly complex phenomena such as convection cells and thunderstorms, while in the case of the above-mentioned particle simulations there is no higher order emergence taking place, nor a fully scientific structuring of the system. If one were to nevertheless compare (since both cases concern computer simulations) this mechanism-independence to the partial accuracy of the RealFlow simulations, this could lead one to question the necessity for a high degree of scientific precision in all material simulation parameters.

3.1.4.3. Properties- Partial Attribution

Here, if one were to hypothetically adhere to the sole use of scientific *properties* (and bearing in mind that these can only be partly attributed in RealFlow), merely attributing the *global* gravity force and individual *density* parameters accurately, would have a direct impact on the rheological behaviour and the blending extent between the two fluids. Gravity would pull the substances downwards towards the -Z axis of the scene affecting their flow, while different densities would also have an impact on flow, as well as altering the degree of blending[35] of the materials. This could in a way relate to the partial model aforementioned, in which only a limited amount of information is enough for a general behaviour to be studied.

3.1.4.4. Values- Additional Attribution

Additionally, if the other material parameters that have attributes internal to the software and to each other (i.e. *values*) were added, then there would be further *qualitative specificity* in the blending observed in the material tests. For instance, if the viscosity parameter has no scien-

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35 The phrase *degree of blending* here, meaning the extent of the fusion gradient, i.e. how prolonged or compressed the graded region between two materials would be.

tific property, knowing that the actual physical value of dynamic viscosity for molten aluminium is different to molten copper, as well as the numeric ratio of this difference, would allow for additional specificity to occur in the fusion behaviour of two or more materials. Of course, something like this relative and internal to the software attribution would have to be referenced against a set of criteria that would determine whether partially using *properties* and partially *values*, would be adequate for the intended design purpose.

3.1.4.5. Criteria & Parameter Attribution

In turn, if these criteria were structural and precision in identifying areas of material concentration was of primary importance, then as many of the inputs as possible would have to be properties[36]. As it will be seen later, however, as far as structural behaviour is concerned this is notoriously difficult to predict on complex multi-material formations. In addition, other parameters, such as the agency attributed in the simulation need to come into play, as this can be the only parameter that can enable the incorporation of the loading conditions acting on a multi-material entity.

3.1.4.6. Parameter Attribution Accuracy

In effect, as simulations are utilised for design purposes (to a large extent informed by structural considerations[37]) within the scope of this thesis, the main objective has been to input all intrinsic properties as accurately as possible (both in a direct, as well as relational manner[38]), with this accuracy stemming from research into physical material properties, as well as the author's experience-based knowledge about materials[39].

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36 Additional criteria here would be a visual and behavioural observation of how the liquids appear and behave physically. These will effectively form an evaluation framework in 6.3.3.2. when analysing the degree of fidelity to physical reality obtained in the multi-material blends generated in RealFlow.

37 As previously discussed, taking into account structural considerations as one of the main design drivers is a result of the solely technical nature of existing functionally graded material literature.

38 I.e. both in terms of properties, as well as values.

39 Whose background is architectural design, and not structural engineering or any other related scientific discipline.

3.1.4.7. Simulation Limitations

Having said that, however, it ought to be recognised that even within the philosophy of science there is an ongoing debate as to what a computer simulation actually is[40], let alone how a simulation should be set up. Effectively, as it will be discussed in Design Study 06, a simulation becomes a much more approximated endeavour (Winsberg, 2015) that is good enough for its intended purpose, as it is impossible to fully and accurately reconstruct *all* parameters at play in a physical environment.

3.1.5. Design Study 04

The next series of tests took aluminium and copper as the digital materials to simulate, a choice that is in connection to Design Study 06 that will follow and since as it will be shown these two substances typically exhibit fusion compatibility. In effect, the purpose of the exercise was to blend the materials in their liquid form, which meant that there had to be a *Liquid Temperature* parameter input in the simulation, as the metals need to be in molten form to mix. Therefore, the RealFlow plugin *HotNCold*[41] was used in this exercise in order to allow for the temperature parameters of the liquids to be set. Consequently, 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. The density and viscosity of the two materials were also attributed: copper at 1200 degrees centigrade has a density of 7,898 kg/m³ and its dynamic viscosity at the same temperature is equal to 0.00312 Pa·s, while for aluminium the values were at 2,375 kg/m³ for density and 0.001379 Pa·s for dynamic viscosity.

3.1.5.1. Ambient Temperature & Blending

During the studies, a cubic mass of the two materials was released on either side of a rectangular container from a low height and a series of iterative tests were performed in order to achieve the mixing of the two substances. What was observed after these initial tests was that when the *Ambient Temperature* was set to 400 Kelvin, the two liquid substances would reach a settled arrangement quite early in the simulation without mixing (Figures 31 & 32). Increasing the *Ambient Temperature* to 2000 Kelvin caused an intense reaction between the two (Figure

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40 This has been concisely summed up by Varenne (2001, p.551) in the form of three prevalent theses : "*Thesis I*: A computer simulation is an experiment", "*Thesis II*: A computer simulation is only a tool", and "*Thesis III*: A computer simulation is an intermediate between theory and experiment". Additionally, Winsberg (2015) provides an informative analysis of the Epistemology of Computer Simulations that discusses different definitions of what a simulation is, their various types and purposes, as well as how they can be verified and validated.

41 *Liquid Temperature* is a parameter not available in RealFlow by default.

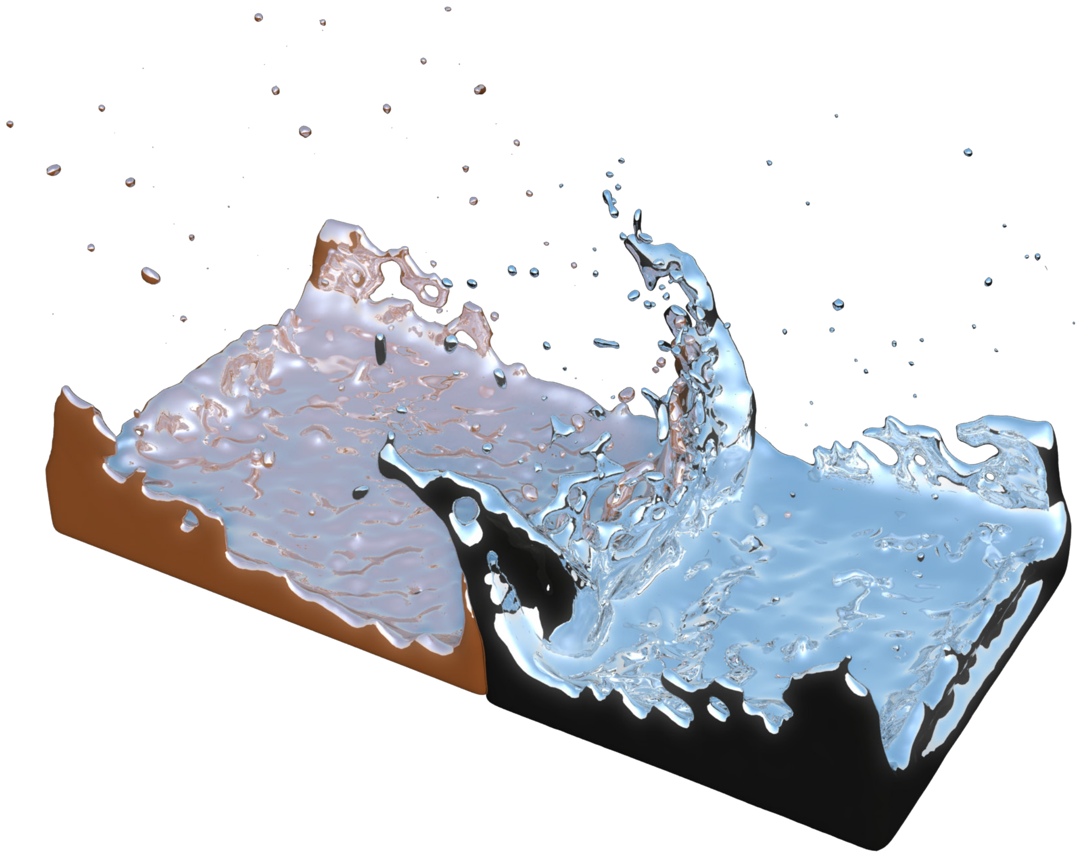

Figure 31: Copper-Aluminium Mixture Simulation Snapshot at 36 seconds. The ambient temperature was set at 400 Kelvin.

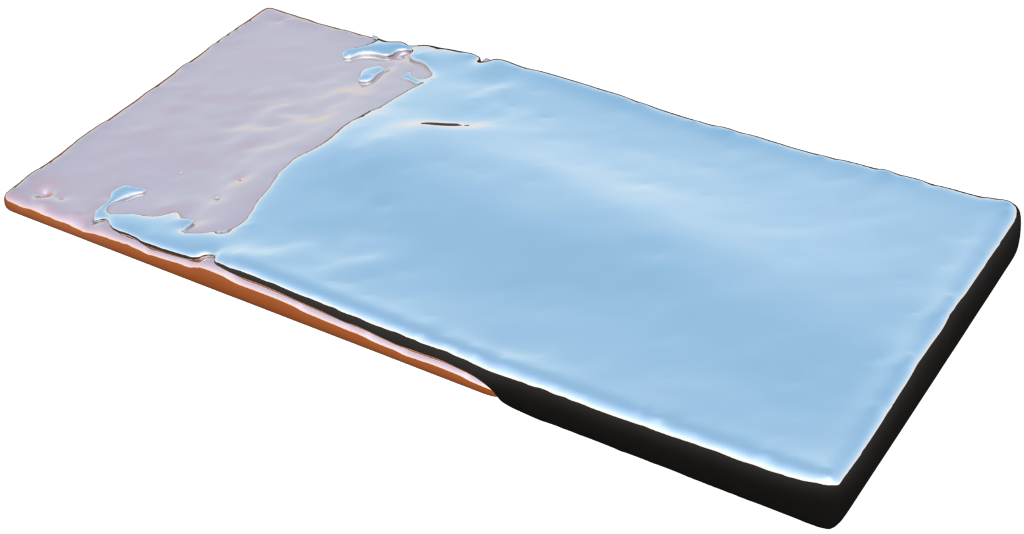

Figure 32: Copper-Aluminium Mixture Simulation Snapshot at 126 seconds.

33) that eventually led to one material settling on top of the other with some gaps being formed within the overall volume of the aluminium (Figure 34).

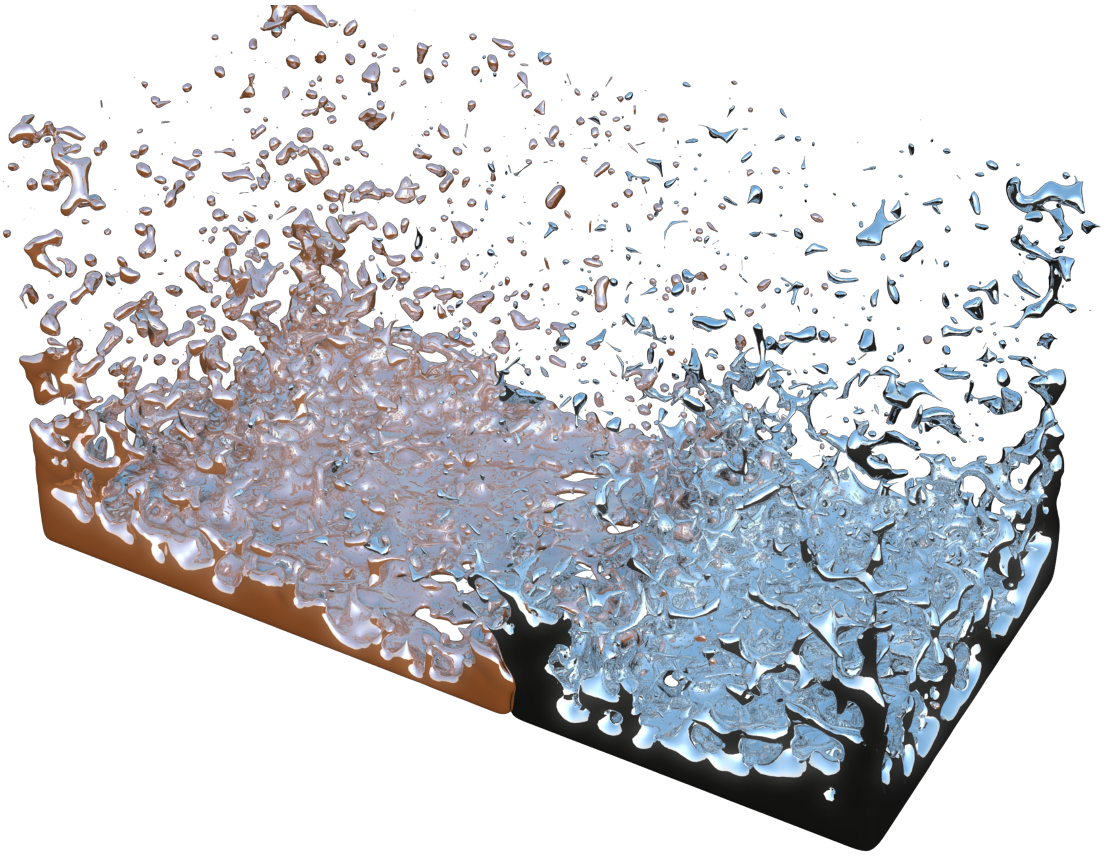

Figure 33: Copper-Aluminium Mixture Simulation Snapshot at 37 seconds. The ambient temperature was set at 2,000 Kelvin.

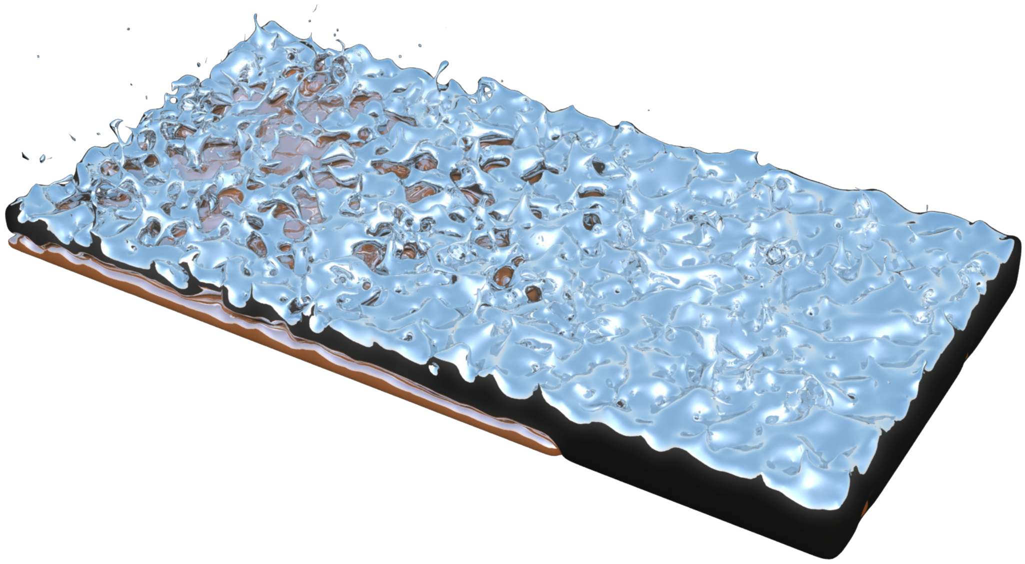

Figure 34: Copper-Aluminium Mixture Simulation Snapshot at 138 seconds.

3.1.5.2. External Agency & Blending

In order to then achieve a gradient blending of the two materials, a number of external forces were applied to the centre of the container to act as attractors with a radial force. Following a series of iterations using a *Vortex* and a *Coriolis* force[42] and despite the fact that integration between the two was more pronounced, the nesting of one substance into the other was not

Figure 35: Bottom View of Copper-Aluminium Mixture Simulation under a Coriolis Force, at 48 seconds.

Figure 36: Bottom View of Copper-Aluminium Mixture Simulation under DSpline Attraction, at 48 seconds.

42 This is an attractor based on the forces generated in the Coriolis effect.

achieved (Figure 35). A final series of tests using a *DSpline* that generates a strong vortical attraction force at the base of the container enabled the materials to have a spiral blending arrangement, with the two radially nesting within one another[43] (Figure 36).

3.1.6. Pre-Blends- Blended Outcome Evaluation

The design exercises conducted so far mainly focused on mixing diverse materials in liquid form using particle simulation software. There was limited success in achieving this, however, mainly as the results exhibited alternating striations of two particle systems A and B without however attaining the blending of the two systems and the formation of gradients in between (Figure 37). By gradients it is meant that—similarly to the definition of continuous graded structure distribution in Functionally Graded Materials (Miyamoto, et al., 1999)—two opposing regions, of solid material A on one side and solid material B on the other, would have to gradually blend into one another with the central part of the arrangement having a 50% distribution of each material.

3.2. Effective Blends

3.2.1. Design Study 05

In response to this definition, and using the above described settings for aluminium and copper it was finally possible to achieve the formation of gradients between the two materials by applying a singular particle mesh over the two systems (Figure 38) (as opposed to using a separate mesh for each particle system as was the case in the previous RealFlow studies). As it will also be examined in 5.2.4.1., this gradient formation takes place as the two particle systems (A) and (B) each have a respective colour, which in this instance can be named colour (A) and colour (B). When the mesh skin is applied over the blended particle formation, an algorithm native to RealFlow[44] reads the closest set of particles to each of the mesh vertices, averages out their colour values and colours the vertex accordingly. A maximum degree of influence of particle system (A) will colour the vertex fully with colour (A), while an equal degree of influence will mean that the corresponding vertex is a blend of colour (A) and colour (B). Multi-materiality is therefore imprinted on this mesh skin as colour graded boundaries in-between the main material areas (represented by different colours) of the mesh volume.

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43 The intent with applying these forces here, was for the two liquids to mix in a gradually integrated, vortex-like manner and not merely form a layer on top of one another.

44 The fact that this algorithm is software specific and rigid in its structure (i.e. not taking into account material properties) poses one of the main limitations of this specific CAD tool and will be discussed further in 6.3.3.3.

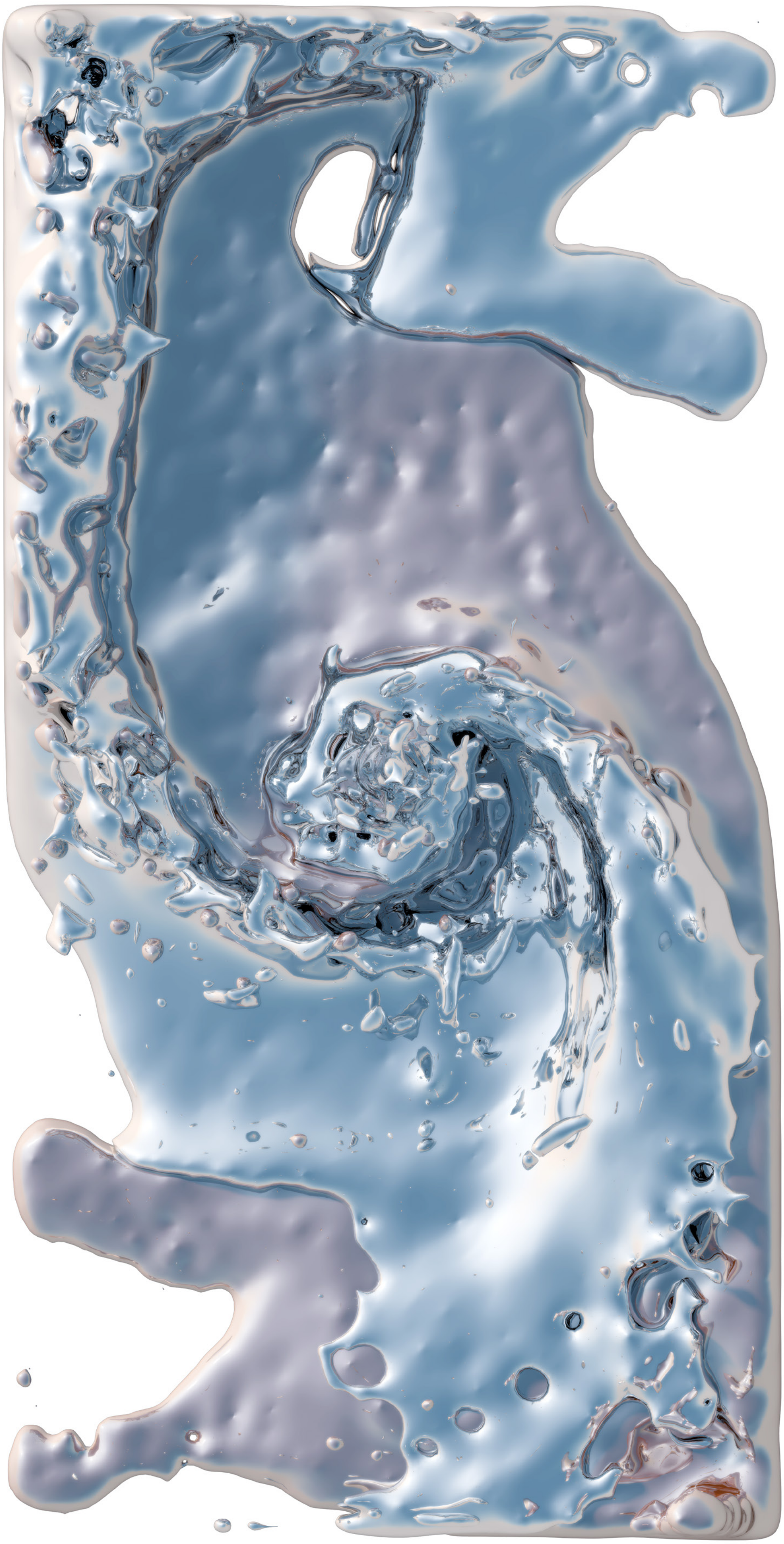

Figure 37: Copper and Aluminium Blending Simulation Using Two Individual Meshes. Snapshot is taken at 48 seconds.

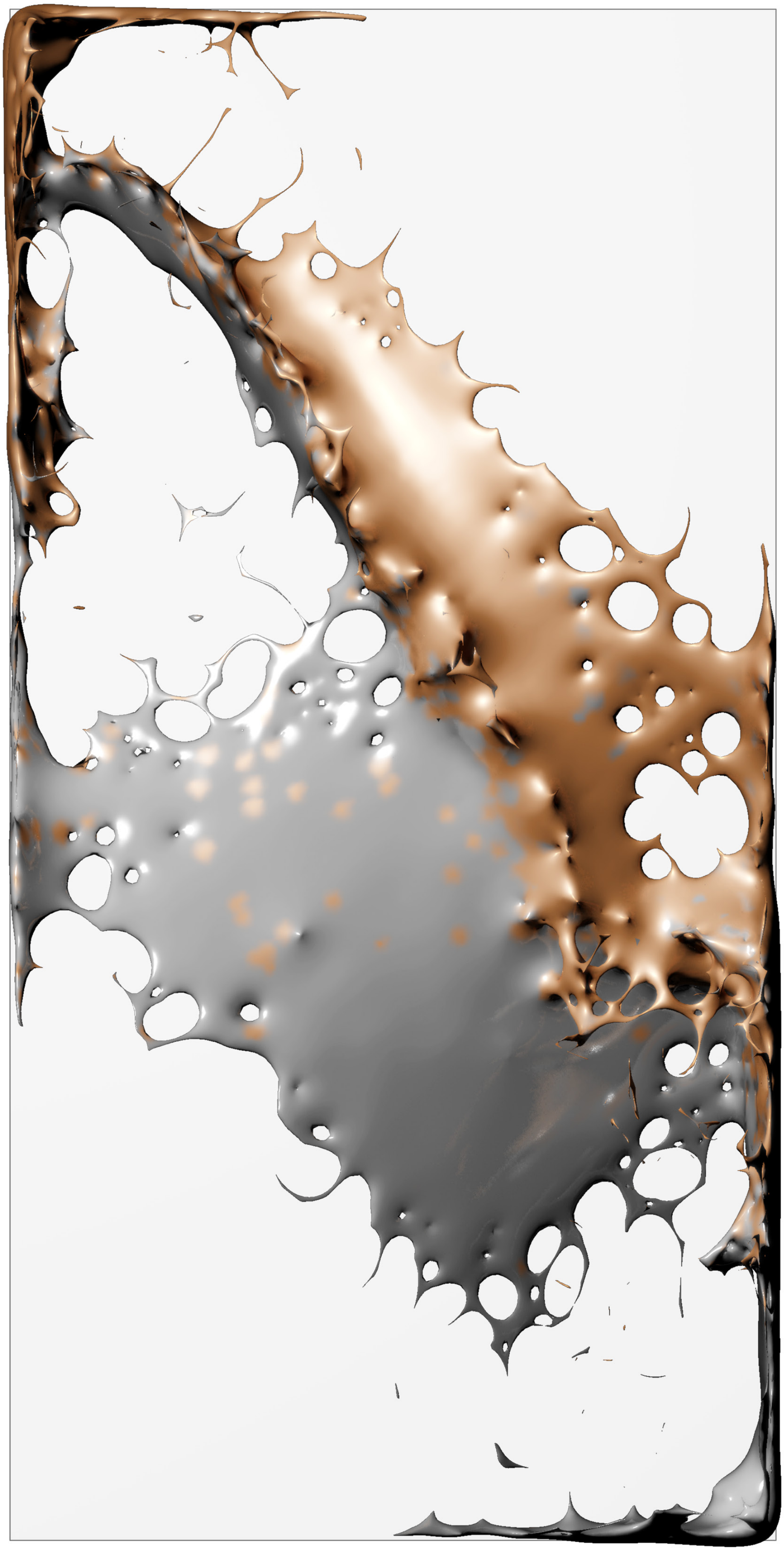

Figure 38: Copper and Aluminium Blending Simulation Using a Single Mesh. Snapshot is taken at 22 seconds.

3.2.2. Thesis Design Methodology- Definition of Main Parameters

Having in this case identified an appropriate computational method for achieving material blends, this technique was applied in the ensuing design studies. More importantly, a direct observation from the previous exercise and a consequence of using particle systems as a CAD tool is that there are three main parameters that affect the way materials are structured in space and fused together. These are going to be analysed in detail in what follows, both in design terms, as well as in regards to the theoretical argument that will be presented in chapter 4.

More specifically, regarding the first of the three parameters, since the materials are of particulate or liquid type, the *form of the mould* that they are going to be contained or poured into is a main design aspect to be considered. Secondly, the *forces* or *agency* that affect the simulation also need to be placed strategically as, in addition to their *intrinsic* propensity, there needs to be a "flow of energy rushing through the system" (DeLanda,1995) for materials to find an arrangement in space. Thirdly, in terms of the materials themselves, the parameter that needs to be considered is the *fusion compatibility*[45] that they exhibit, as non-chemically compatible substances could be simulated in the computer but not fabricated physically.

3.2.3. Thesis Design Originality- Lineaments Versus Material Cooking

Effectively, and in terms of the originality of the thesis (apart from the aforementioned novel use of computational fluid dynamics to design multi-materials with) the focus is shifted here from the design practice of "*drawing as an assembly of 'lineaments'* [emphasis added]" (Ingold, 2013a, p.125) towards the one of c*omputational material* "*cooking in a bag* [emphasis added]" (Lynn, 2010, p.19).

More specifically, the line and plane that delineate spatial boundaries have typically been the main representation tools of a design thinking that revolved around the creation of enclosure in binary sequences of void and infill. This practice of using "lineaments" (*lineamenta*), to specify the form of a design or building and that "on paper […] would have been inscribed as drawn lines […] and […] understood […] as the geometric projection of a conceptual image" can be traced back to Alberti and his "unequivocal commitment to the hylomorphic model of making" (Ingold, 2013a, p.50).

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45 There are already research initiatives like the Materials Project set up by The Computational and Experimental Design of Emerging Materials Research (CEDER) Group at the University of California, Berkeley that consists of a virtual material library that "aims to compute the properties of all known materials and […] improve software's predictive capabilities for new material combinations" (Drazin and Küchler, 2015, p.273). The fusion compatibility between materials in the thesis is established through 'manual' research, but there could be a possible scenario in which material databases such as the one of the Material Project are directly 'plugged into' the simulation environment, in order to verify multi-material compatibility in real-time.

3.2.4. Intrinsic & Extrinsic Forces

Instead, the design method that will be discussed in more detail in what follows, "is the outcome of a complex interplay of forces, both internal [*intrinsic properties and values*] and external [*mould form and assigned agency*] to the material", where the "properties [of the substances to be fused] are directly implicated in the form-generating process" (Ingold, 2013a, p.51). This also relates to the observation that "to say that 'material flows', is to ascribe to it a tendency do [sic] so, implying endogenous properties that make this possible, as well as external forces that activate these properties, akin to gravity without human agency[46]" (Drazin and Küchler, 2015, p.123).

3.2.5. Non-Controlled Control & Main Design Points

What is effectively argued for, 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[47], a direct approach that integrates properties as part of the design process is crucial. Representation should be avoided, for a process where the physical can be simulated in the digital realm, in essence allowing for a closer relationship between the two. Design in this instance should acquire a loose type of control or something akin to "controlling, but resisting control" (Wiscombe, 2010, p.21). Its function should be to generate an enclosing framework within which, matter will be allowed to self-structure and different substances fused together into continuously graded topologies. There should therefore be a thin balance between designing these frameworks and enabling self-arrangement. In effect, all these can be summed up in the following points:

a. Departing from tectonics, the basic claim is that *fusing* is the appropriate technique linked to twenty first century graded material types and multi-material fabrication.
b. Fusion in turn, enables a novel way of designing directly with *liquid, mouldable matter* in digitized form.
c. The design process corresponding to this practice should be about *establishing a framework and a set of relations*, i.e. designing the extrinsic circumstances for form and gradients to emerge from within materiality.

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46 The question of human agency is one of the main subjects extensively discussed in 4.3.7.

47 The current limitations of this will be presented in 5.2.

3.2.6. Design Study 06

3.2.6.1. Design Study 06- Simulation Parameters

Consequently, and in terms of the above-mentioned three parameters that need to be considered in designing fusion, the investigation that follows was directed towards specifying how can *a. the material type* and *b. the affecting agency* parameters input in the simulation be assigned.

3.2.6.2. Simulation & Reality

When describing their argument in favour of the epistemological dependence thesis (which suggests that the degree to which simulations can be valid, depends on the degree of their resemblance to experiments), Stephen Norton and Frederick 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). In response to this, Eric 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 will be utilised for design rather than scientific purposes. What can be therefore argued on this level, is that the endeavour in what follows has been for these formal relations to be present in the form of simulation parameters assigned in the computer resembling physical material properties and values as closely as possible, and of the simulation forces being informed by practised FGM manufacturing methods and/or 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 arrange themselves and fuse.

3.2.6.3. Accumulative Roll Bonding Multi-Material Manufacturing

In terms of the industrial manufacturing methods, Schmidt et al. (2012, p.1009) describe their technique of designing "graded materials by particle reinforcement during accumulative roll bonding" according to which, aluminium sheets are 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 repeatedly (Figure 39), generating a sandwiched material consisting of copper particles gradually placed in layers within the aluminium body (Figure 40). The benefit 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 material property gradient can be distributed in a manner that can be "directly opposed to the gradient in loading condition" (Schmidt, et al., 2012, p.1009), therefore having a direct impact on the structural performance and amount of material used in the sheet (Grigoriadis, 2014).

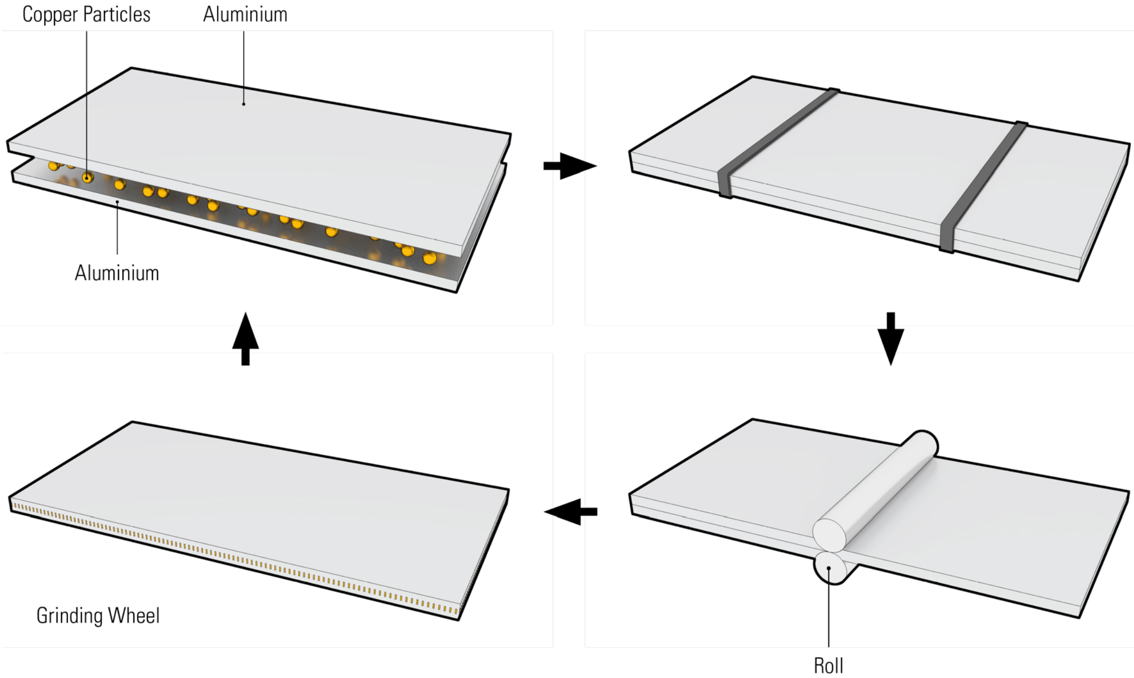

Figure 39: Diagram of the Accumulative Roll Bonding Process, for reinforcing an aluminium sheet with copper particles.

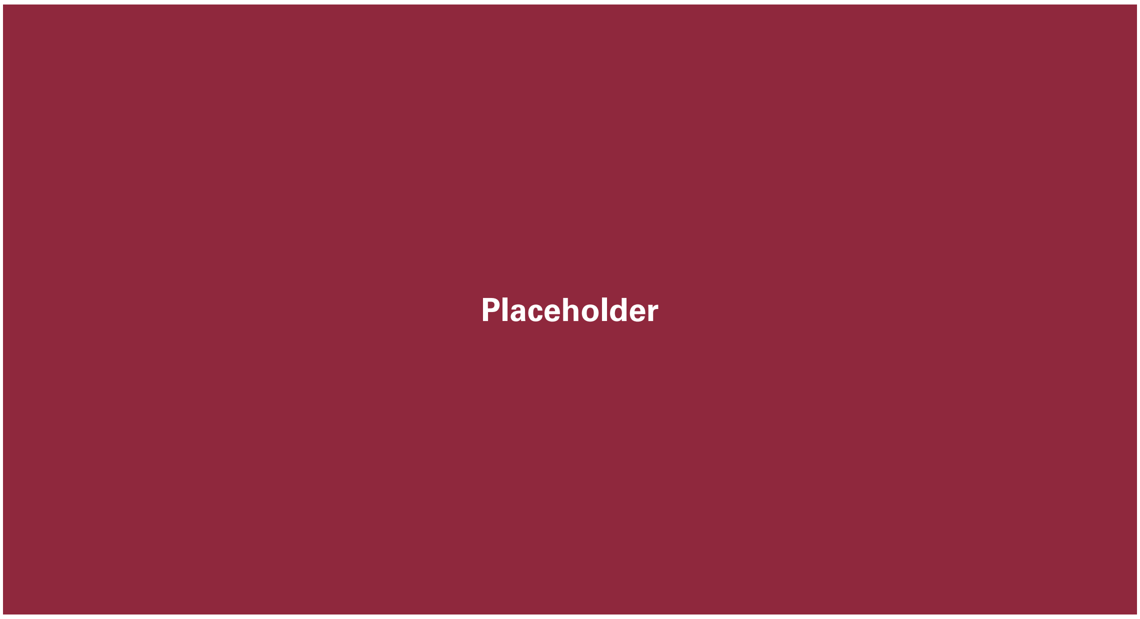

Figure 40: 3D Computer Tomography Visualisation of the Copper Particles, roll bonded within the aluminium sheets. The curved end of the specimen on the right is due to the imperfect cutting of the sandwich sheet.

3.2.6.4. Material Type Selection

As the intent here has been to define a model that simulates real world material gradients, the selection of materials in this instance has been determined by their existence as part of a physical multi-material entity. The technique by Schmidt et al. (2012) verified that aluminium and copper bi-materials do exist physically[48] and the two substances have therefore been utilised in order to design a panel hypothetically exposed to a high wind flow velocity condition.

3.2.6.5. Design Objectives

With this in mind, a *first* objective has been to decrease the amount of overall material that would otherwise be used for a conventional aluminium panel. A *second* objective has been to allow for openings on the surface of the sheet that cover approximately 25% of the total surface area[49] (Government of Saskatchewan, 2016), which would partially allow wind through the element. Primarily, however, the main objective has been to answer point *b.* and to establish the appropriate forces (or *affecting agency*) that should be employed in a material blending simulation.

Effectively, starting the design process off, a direct frontal wind was simulated for velocities of 90 km/h and a pressure map indicated the load distribution on the surface of the sheet measured in Pascal units (Figure 41). The intent was then to assign the material properties of the two substances in the simulation environment and in their molten form. Here, the materials being the same as the ones in Design Study 04, the identical parameters were set for the two substances.

3.2.6.6. 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 forces attributed were *Limbo daemons*[50] that effectively are two notional planes that constrain the movement of particles in the space between them. This was in order to achieve a more fitting resemblance to the manufactured sheet that had the bulk of copper reinforcement horizontally spread in-between and across the aluminium body. The first simulation was eventu-

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48 This is also the case in aluminium bronze alloys that are mixtures of aluminium added to copper.

49 This figure derives from the fact that a potential use for the redesigned panel could be as 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.

50 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.

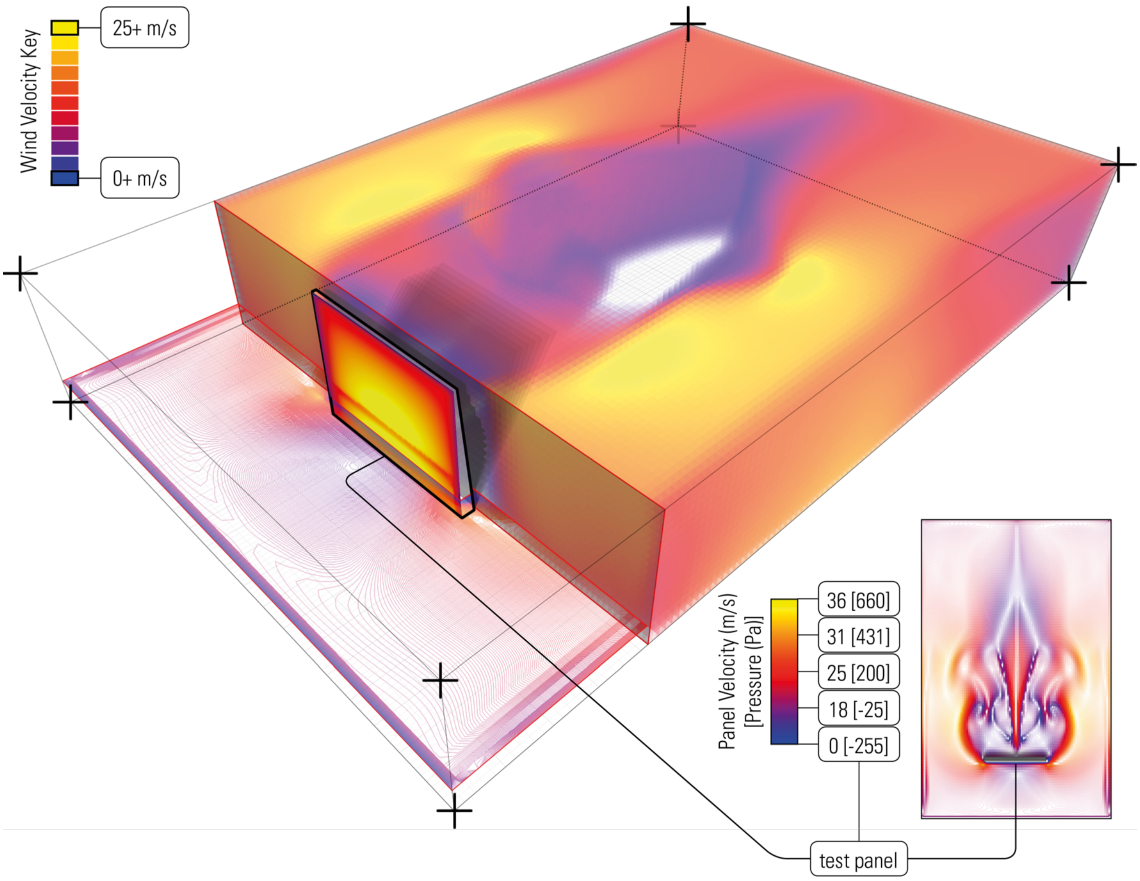

Figure 41: CFD Simulation on the Sample Panel, showing tensile load intensity on the panel's surface.

ally set out with three aluminium and one copper particle emitters placed within a container and allowed to run until the copper accumulated gradually and horizontally across the middle of the aluminium matrix (Figures 42 & 43).

3.2.6.7. 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% (Figure 44). In this case the structural objective would be met as it is envisaged 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%.

3.2.6.8. Limbo Agency Critique

A main issue, however, in this first exercise was that the *agency* assigned was not stemming from the physical domain. More specifically, there were forces acting on materials individually[51],

51 One of the Limbo forces was linked to affect the copper and one of the two aluminium (al-

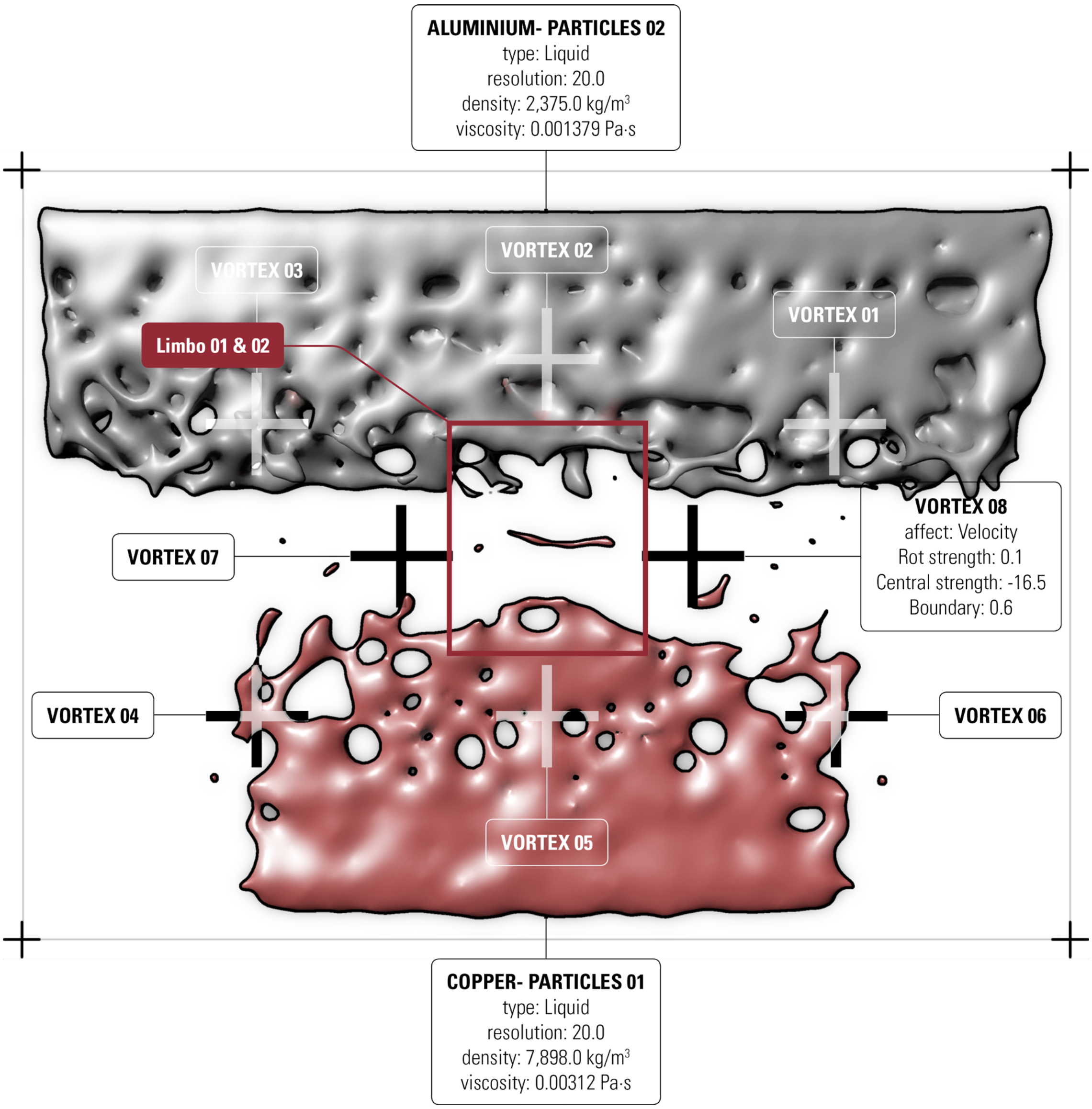

Figure 42: Copper Aluminium Blending Simulation Snapshot at 12 Seconds, showing the positioning of the forces affecting the two fluids.

which although can be a possibility (with an example being magnetic forces acting on ferrous materials only), in this instance the forces were software specific and selectively applied rather than reality based (Figure 45). Further research on manufacturing techniques can verify whether the creation of forces of this nature can be attained, but in this case, it has been assumed that the use of Limbo forces would be against the objective of bridging the virtual to the actual.

3.2.6.9. Invasive versus Non-Contact Forces

Additionally, regarding this material arrangement in a physical environment, it can be argued that the accumulative roll bonding process described above is contrary to the idea of self-struc-

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uminium 01) particle systems, while the other Limbo force was linked only to the other aluminium (aluminium 02) system, hence the non-realistic, selective nature of the agency.

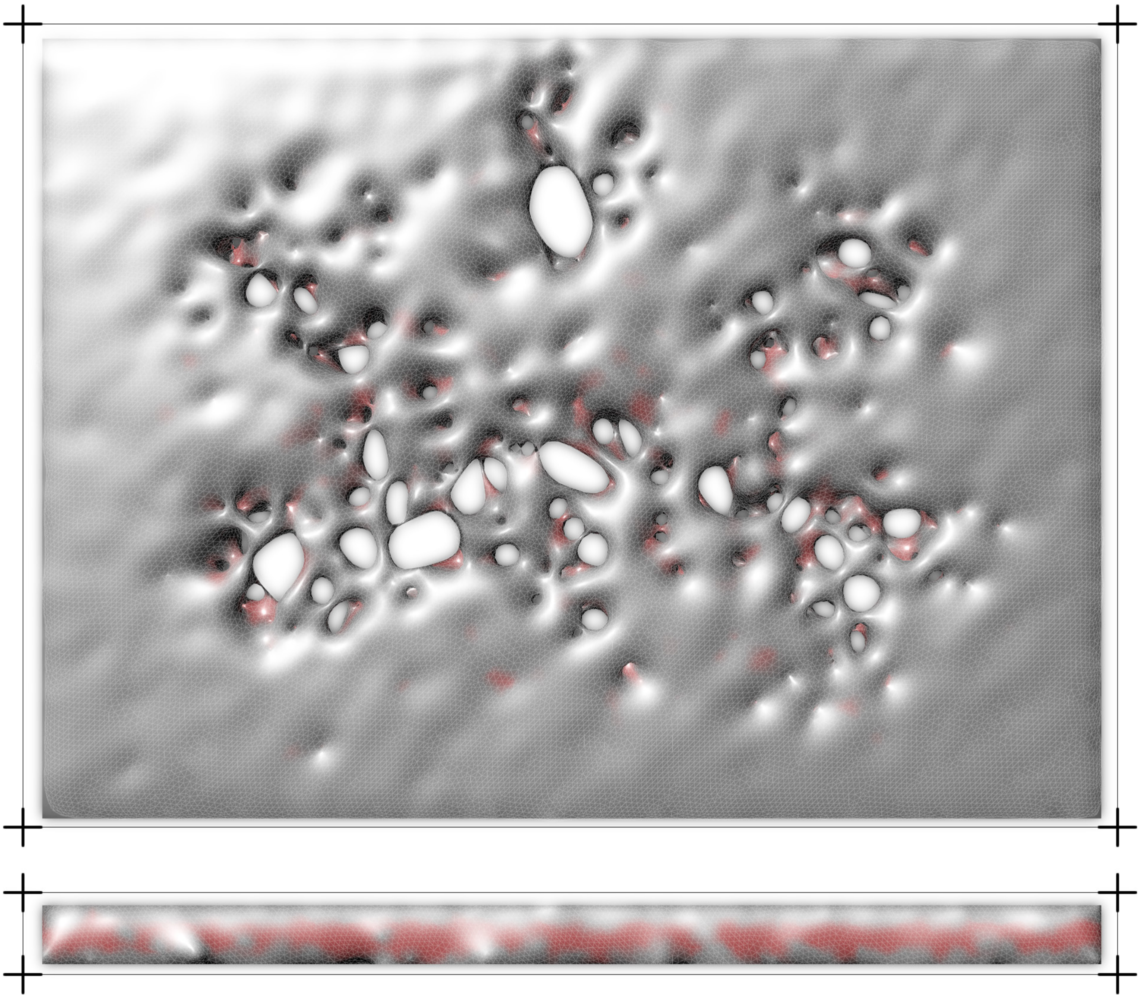

Figure 43: Front and Side Views of Copper Aluminium Blending Simulation, taken at 97 Seconds. The bottom view shows the sandwiching of the copper particles (red) in between the aluminium (silver).

turing. The treatment of aluminium and copper during the forceful, energy-consuming, severe plastic deformation process that takes place during roll bonding is counter to the principle of *intrinsic* fusion under *non-invasive* forces. The term *invasive* would equate in this case to a machine, tool, physical part or solid apparatus that coerces form on the two materials and that is directly synonymous to the imposition of "form [...] upon a material" (Ingold, 2013a, p.21). The difference to the *non-invasive* is that industrial machinic force cancels out the intrinsic chemical-bond capability of materials blending together under centrifugal, gravitational, magnetic and other *non-contact forces*.

3.2.6.10. Acceptable Agency

In addition, when looking into this problem architecturally, the main acceptable force that requires no justification for its application on a material entity would be gravity. For another *non-contact force* to be allowed to act on a material fusion simulation it needs to come from anticipated structural and environmental loading conditions on a particular segment of a larger multi-material entity. This additional force can be there to simulate and accelerate these loads in

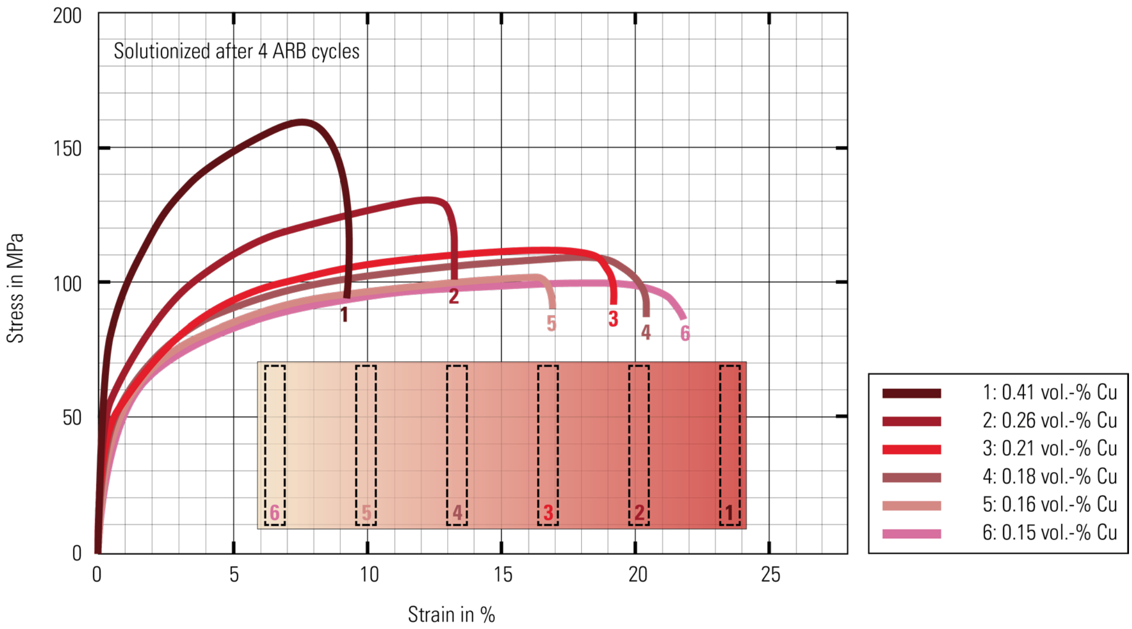

Figure 44: Tensile Strength Graph, for specimens of different copper content across the aluminium sheet.

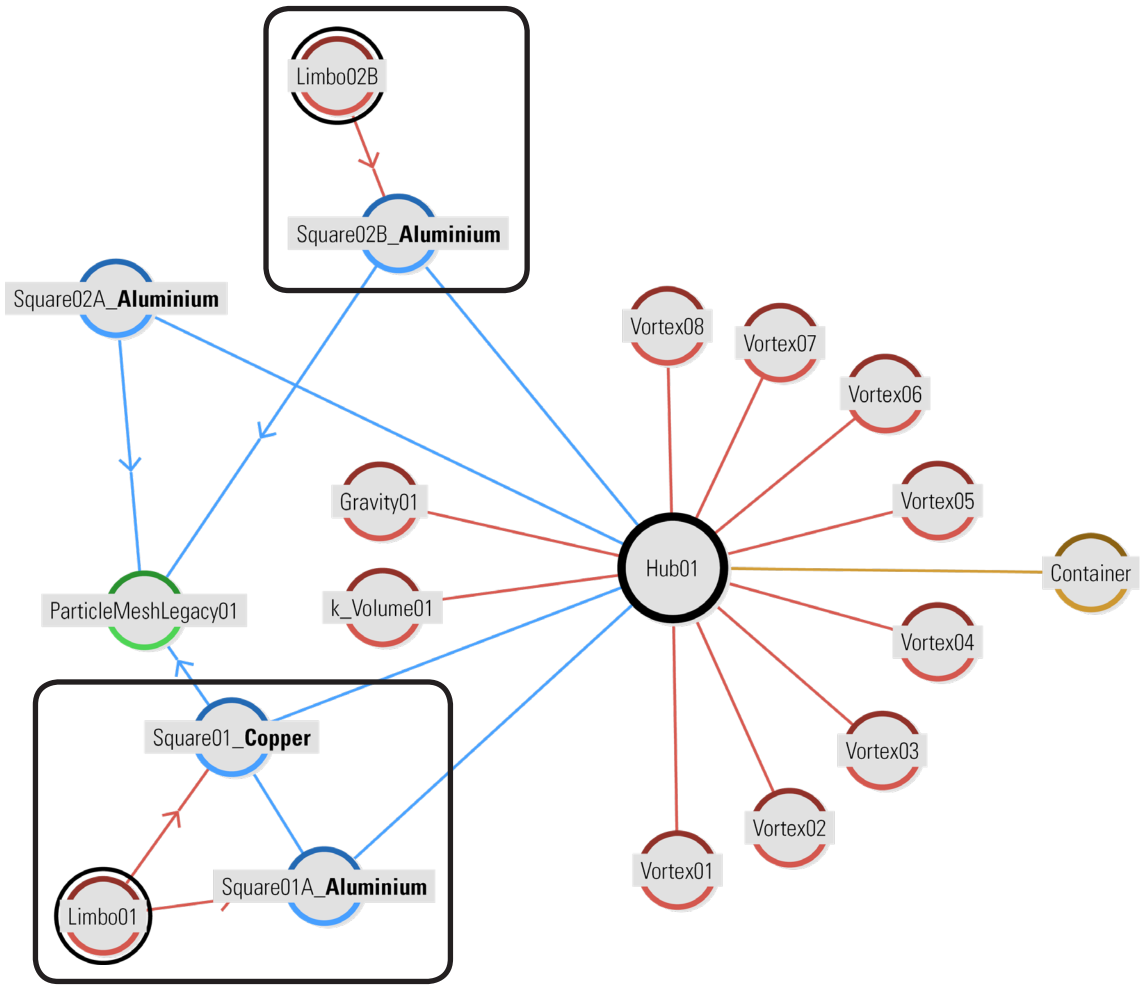

Figure 45: RealFlow Relatioship Editor Screenshot. Most of the forces (red circles) are connected to the simulation hub (black circle) and therefore applied globally. Highlighted within the black frames, are the exclusive links of forces acting on particles (blue circles) selectively.

the computer, with the result being a 'natural' arrangement of individual substances in the multi-material space. Effectively, this is "not an imposition of form on matter but a bringing out of forms, more topological than geometrical, that are latent in the variation of the material itself" (Ingold, 2013a, p.45). Or as Simondon (1989, p.304) posed, this:

> "is not to be thought of as the meeting of a previous form and matter existing as already constituted and separate terms, but a resolution taking place in the heart of a metastable system rich in potentials: *form, matter and energy pre-exist in the system* […] At the same time that a quantity of potential energy (the necessary condition for a higher order of magnitude) is actualized, a portion of matter is organized and distributed."[52]

An example of these loading conditions in effect, can be the aforementioned instance of the wind loads on the aluminium sheet. The wind applies force at the centre and is then deflected upwards and at the back of the panel, generating a tensile force that is exerted against gravitational pull. This can simply be represented in a digital simulation by an *attractor* or *vortex force*.

3.2.6.11. Agency Informed by Loading Conditions

A second simulation was therefore run in which the gravity force was preserved and the *Limbo* forces applied in the first simulation removed. In place of these, the second (in addition to gravity) force that would be needed for a gradient to form between the two materials and that was placed in the environment was the aforementioned *vortex* that generated a centrifugal like force at one end of the container that the materials were poured into. The existence of this in the simulation, as well as its magnitude, were informed (apart from their aforementioned similarity to the wind's tensile force) by industrial casting methods for the creation of continuous gradations in FGM (Watanabe and Sato, 2011)[53] (Figure 46). This procedure involves a preheated spinning mould that contains one material into which another molten material is poured. The centrifugal force generated during processing, forces the two at the opposite ends of the

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52 It is also relevant here to quote Skylar Tibbits (2016, p.11), who states that: "researchers in materials science are using a technique called "directed self-assembly" to guide particles into novel configurations and discover new material properties simply by subjecting them to different patterns of energy and letting them configure themselves into useful structures."

53 Here it ought to be stated that linking the attribution of agency to FGM manufacturing methods is based on the assumption that this would be the technique for fabricating the sheet physically. This is also in light of the limitations that are presented in subchapter 5.2. in regards to the available sub-materials in 3D printed multi-materials. Should the 3D printing technology in the future allow for the direct fabrication of an aluminium-copper FGM, then the correspondence of agency to centrifugal casting in this case would not be necessary.

Figure 46: Centrifugal In-Situ Method for Manufacturing FGM. A molten metal is poured in a spinning mould with the centrifugal force separating aluminium (dark grey) from aluminium-copper particles (light grey), during the solidification process. The 100 μm samples on the bottom right are from the inner, middle and outer regions of the mould and show the particle density differentiation. Graph on the left shows the "liquidus temperature of the master alloy being lower than the processing temperature" (Watanabe and Sato, 2011, p.138) and the decreasing of this during the in-situ process.

mould, (which occurs due to the difference in their respective density properties) and eventually a gradient is formed between them.

3.2.6.12. Design Study 06- Evaluations

With these in place, the simulation run achieved the distribution of copper particles to an area that was approximately the same as the tensile loading area output from the wind simulation (Figures 47 & 48). The resulting multi-material sheet was solid copper at the lower end and solid aluminium at the top, while the percentage of openings (approximately 23%) was also close to the objective of 25%. What was evident in this case where the materials were given relative freedom to find their own arrangement in space, was that the resulting formation had altogether different qualities from the aforementioned roll bonded sheet. This was due to the use of the attractor force that resembled much more closely the loading condition on the panel, and even more appropriately corresponding to the FGM manufacturing technique of utilizing centrifugal force to generate material gradients. This has effectively answered research question *b.* regarding the appropriate agency employed in the particular blending simulation.

3.2.7. Effective Blends- Critique

It is apparent from the above that the parameters that affect matter are the central problem when simulating material blending. The problem with existing design simulation software, is

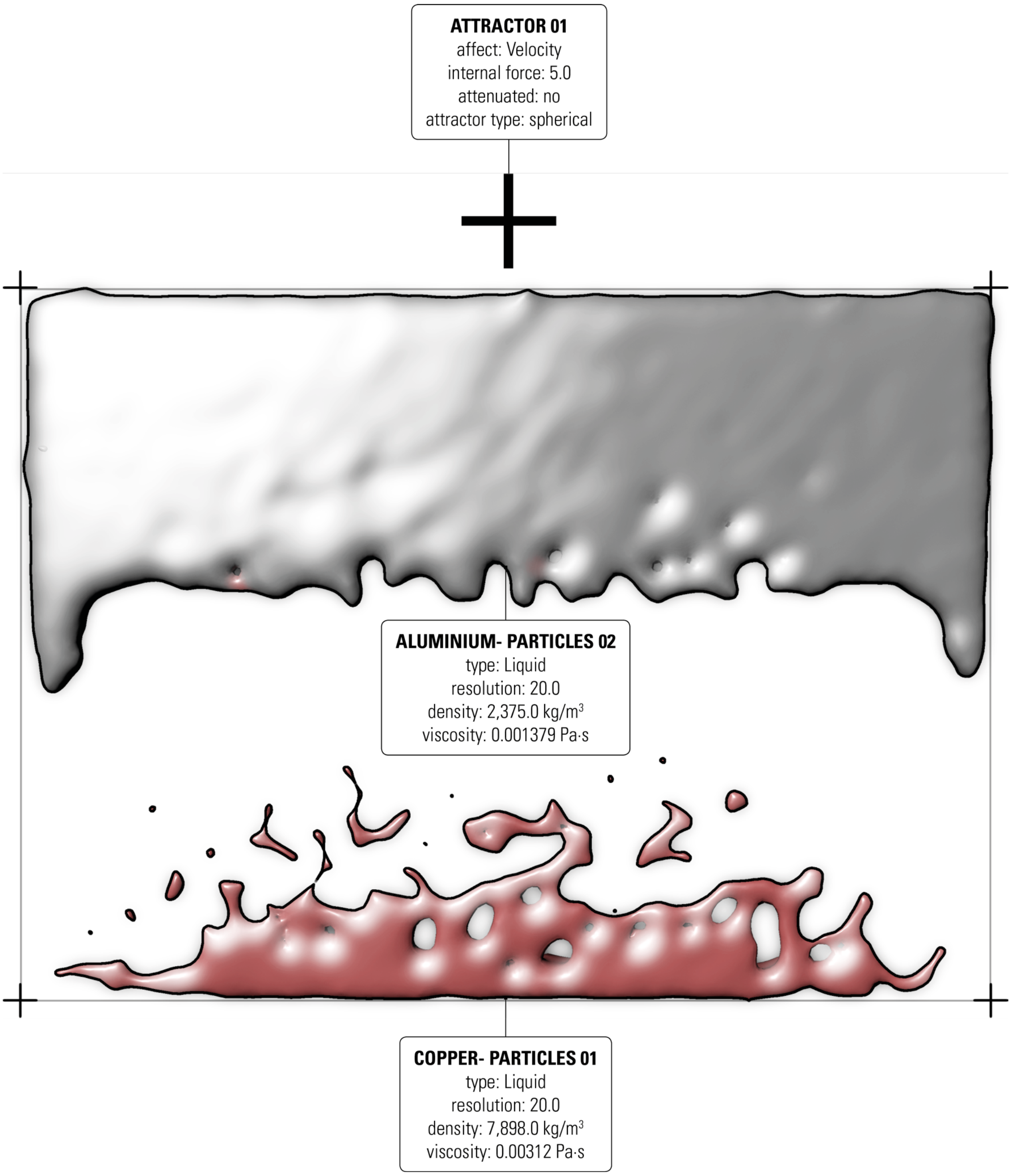

Figure 47: Copper Aluminium Blending Simulation Snapshot at 12 Seconds, showing the positioning of the vortical attractor at the top.

that although accurate to an extent there are in-built capabilities that can enable operations and generate results that can be said to be computer rather than physical phenomena.

3.2.8. Thesis Design Methodology- Design Concerns

A *first* concern of the designer would therefore be to discern the solely virtual from the virtual-but-physically-linked capabilities. The method that has been proposed for this discernment is to research on industrial multi-material manufacturing techniques and/or to work out applied loads in order to make the simple claim that the forces utilised/applied there can also be attributed into the computer. A second concern in this instance would be that a designer "inhabiting

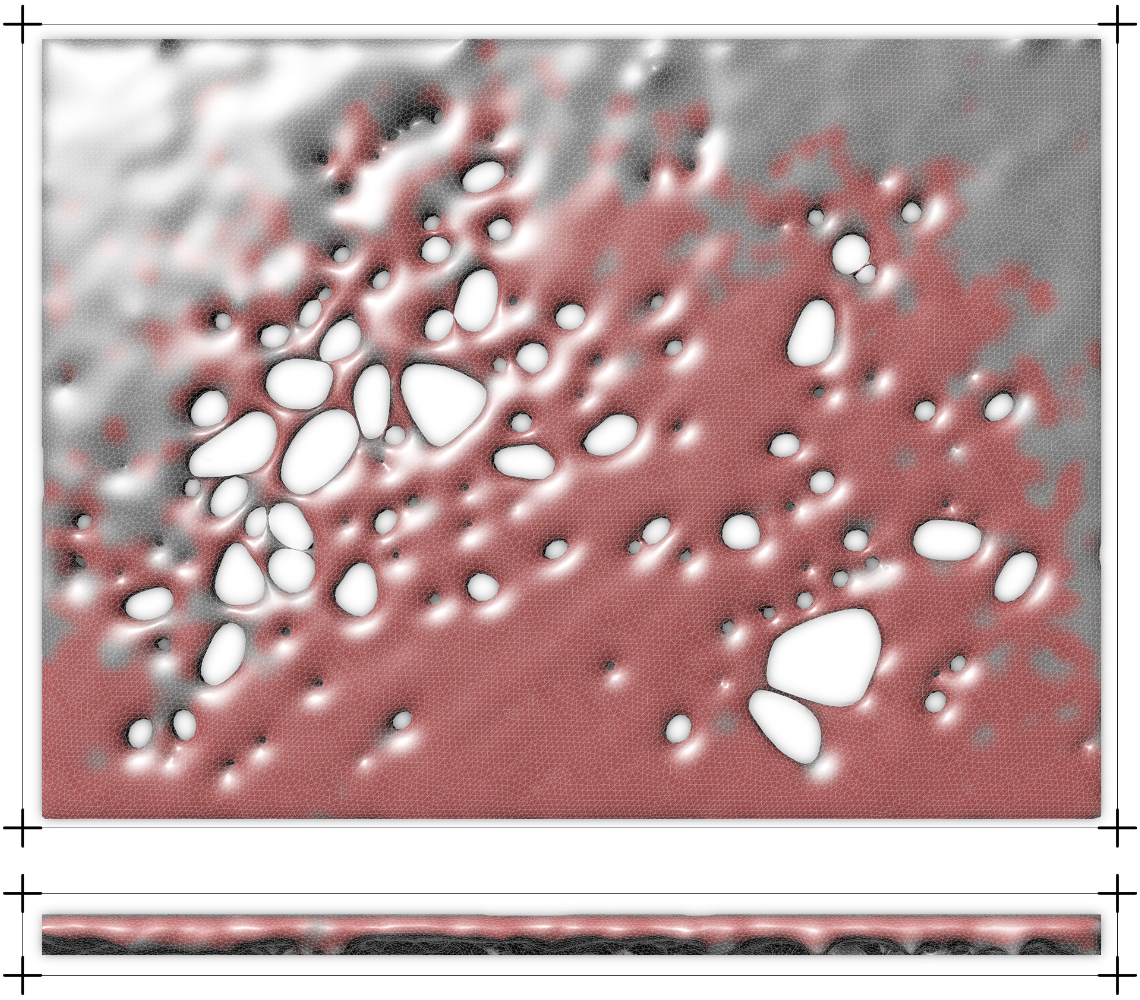

Figure 48: Front and Side Views of Copper Aluminium Blending Simulation, taken at 79 Seconds. The openings cover approximately a quarter of the total surface area of the panel.

a realm *in among* [...] rather than *above and beyond*" (Ingold, 2013a, p.69) form and material, where substance and form inform and conform together (see chapter 4.), would have to divide these manufacturing techniques to *contact* and *non-contact*, *intrusive* and *accelerating*. Once the appropriate agency characteristics have been selected, the *third* concern is whether they can be input in the computer in a one to one measured manner or they need to be approximated. In the latter case the problem that arises is when the material results of the approximated are different to the results of the real. This is especially because particle-based design simulations can only simulate a limited range of scales (Winsberg, 2015), as opposed to multi-scale parallel simulations that can accurately reproduce the quantum, micro, as well as visible scales (this will be discussed more extensively in 6.3.3.5.). 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 will be a constant drive, while at the same time being incessantly conscious of the unavoidable resort to approximation.

3.3. Main Blend

3.3.1. Curtain Wall Interface Design- Task Definition

Moving into the main design focus of the thesis that was outlined in 1.6.4., the following will be analysing the workflow that was followed in order to redesign through a multi-material, the interface of glass to its adjacent aluminium frame in a curtain wall panel.

3.3.2. Curtain Wall Interface Design- Simulation Parameters

Following up on the previous design studies, the two main parameters that will be discussed more extensively are, *a. what are the formal characteristics of the mould*[54] within which materials will be 'poured' digitally and fusion simulated, and *b. what material sub-sets* will form this multi-material entity. In addition, the agency that is attributed in the simulation that is of a similar nature to the one in Design Study 06 will be briefly touched upon.

3.3.3. Material Type Selection

In terms of the selection of materials, as described in 3.2.6.4., the objective of the design experimentation is 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.,

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54 In the case of the Design Study 06, this was a rectangular container the dimensions of which were the same as a standard aluminium panel and therefore not directly implicated in the simulation set out. Here, the attributes of the mould will be discussed in more length, but at the same time as it will be argued for, this will by no means be a top-down approach in which form is treated in an isolated manner and precedes by being disengaged from materiality.

Figure 49: Glass- Alumina & Alumina- Aluminium Graded Material Samples. Image on the left shows the distribution of alumina (white spots) within the glass matrix (red scale bar on the bottom right is 500μm). Image on the right shows the microstructure of the dispersal of zirconia (light grains) within alumina (dark grains) and aluminium titanate (grey grains) (red scale bar on the bottom right is 10μm).

2007, p.134) (Figure 49). With this in mind, it would be theoretically as well as technically feasible to use alumina as an interface material subset in an aluminium-alumina-glass multi-material entity. Effectively, this partially resolved the problem outlined in 1.6.2.1, regarding the amount 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 a centrifugal casting operation (or 3D printing in the near future), 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.

3.3.4. 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 detail consisting of a double-glazing pane affixed to an aluminium frame[55]. The main design concern, here, has been in terms of the appropriate formal characteristics that would allow for a more effective

55 As it will be extensively analysed in the ensuing chapter, starting off with a mould form based on the characteristics of an existing cladding panel (and of the enthesis), is merely for the purpose of illustrating the method of constructing the simulation set out and is by no means to be taken as a fixed starting point. This also relates to the argument that will be made, that one could reverse the whole process by beginning with a material simulation-first approach where material behaviour is firstly observed and then form is gradually made to evolve and conform to this behaviour.

transfer of loads between glazing and structural frame. It was hence deemed necessary to firstly look into examples where graded connections achieve this load transfer in a successful manner.

3.3.4.1. Graded Materials in Nature

According to Shiota and Miyamoto (1997, p.7) "natural materials found in living organisms are composed of graded or nonuniform structures and textures". In fact, the vast majority of connections in nature are functionally graded (Rawlings, 2002) and have resulted "from a long 'trial-and-error' process likely driven by evolutionary selective pressures" (Studart, 2013, p.4423).

3.3.4.2. 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 (Figure 50), utilize a range of ingenuous "mechanisms for overcoming the mechanical mismatch"[56] (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 together. In order 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. In relation to the above point, when the two types of materials are seen in isolation and over specific segments of their volume they are characteristically unique sets of discrete materials. When they are analysed having taken the enthesis into account, however, then muscle, tendon and bone seize to exist as discrete parts and form instead a *continuous multi-material* superset varying its consistency throughout. A very large amount of literature has covered in more detail how this load dissipation is achieved, but overall the aforementioned mechanisms operate on four main levels that are namely organ, tissue, fibre and micro-scale.

3.3.4.3. Enthesis- Macro-Scale Mechanisms

The main aim therefore for configuring the materials at their point of fusion has been 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. According to Benjamin, et al. (2006,

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56 These mechanisms also minimize the radial stresses that typically develop across the connection (Studart, 2013).

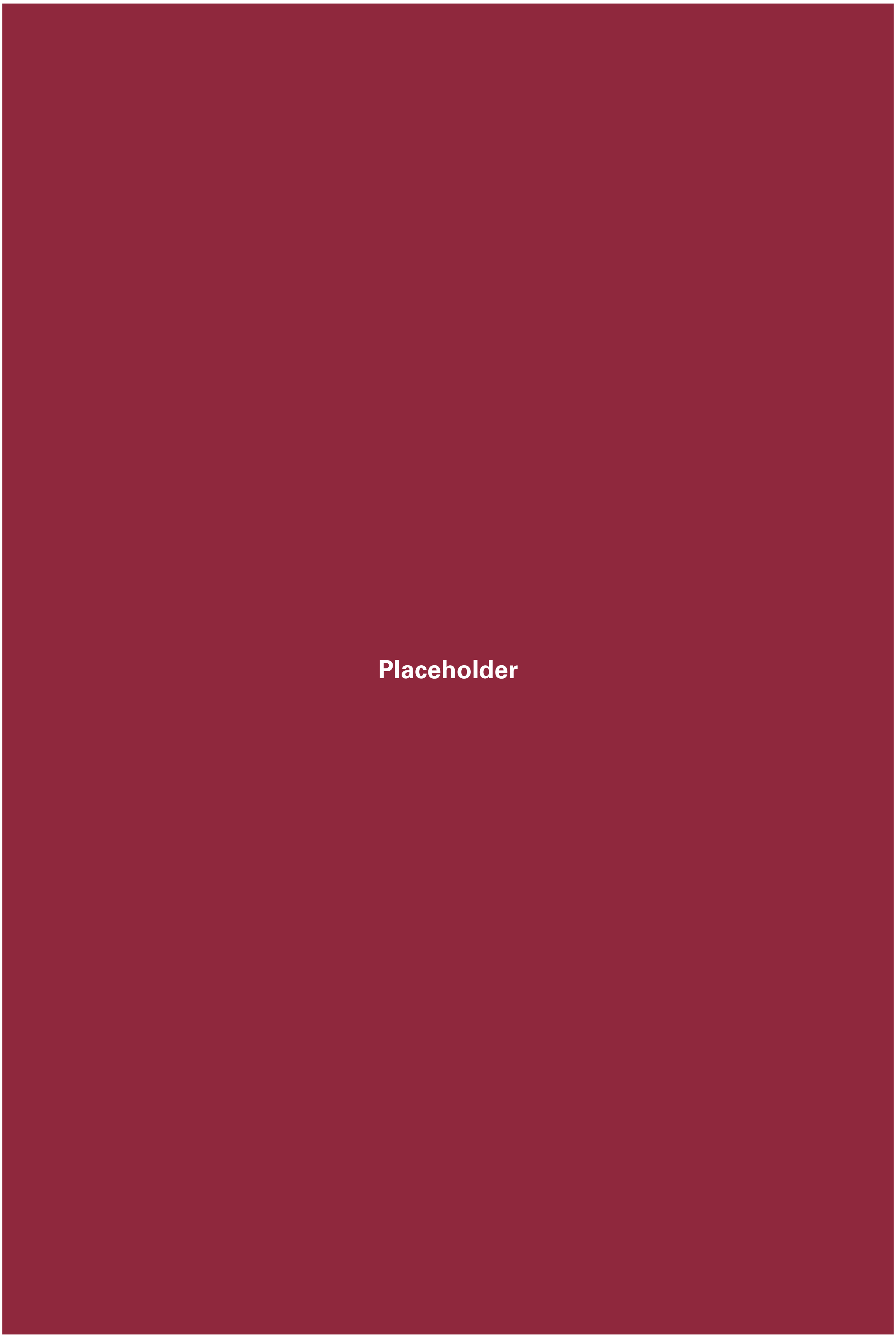

Figure 50: Image of the Enthesis Fibrocartilage, at the point of insertion into the osseous tissue. Visible is the interdigitation between the two.

p.479) "…most tendons and ligaments do not attach to the skeleton in an isolated manner. The enthesis of one often blends with that of another, so that many bony attachment sites overlap

Figure 51: Sagittal View of Anteromedial Ligament Bundle Connection to Shinbone. Particularly visible is the intense interdigitation between the two, highlighted in the region within the frame. Scale bar equals 1mm.

and this adds to the stability of the anchorage." In addition, "what may appear to be discrete muscles are mechanically linked to each other by fascia that establish important lines of force transmission" (Benjamin, et al., 2006, p.479). 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). This junction point is effectively scalloped to "increase the bonding between the tissues" (Benjamin, et al., 2006, p.479) (Figure 51). 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 one 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 have therefore been 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 52). This effectively accommodates 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.

3.3.5. 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 and partially utilised to inform the design operation presented. Whether the sophis-

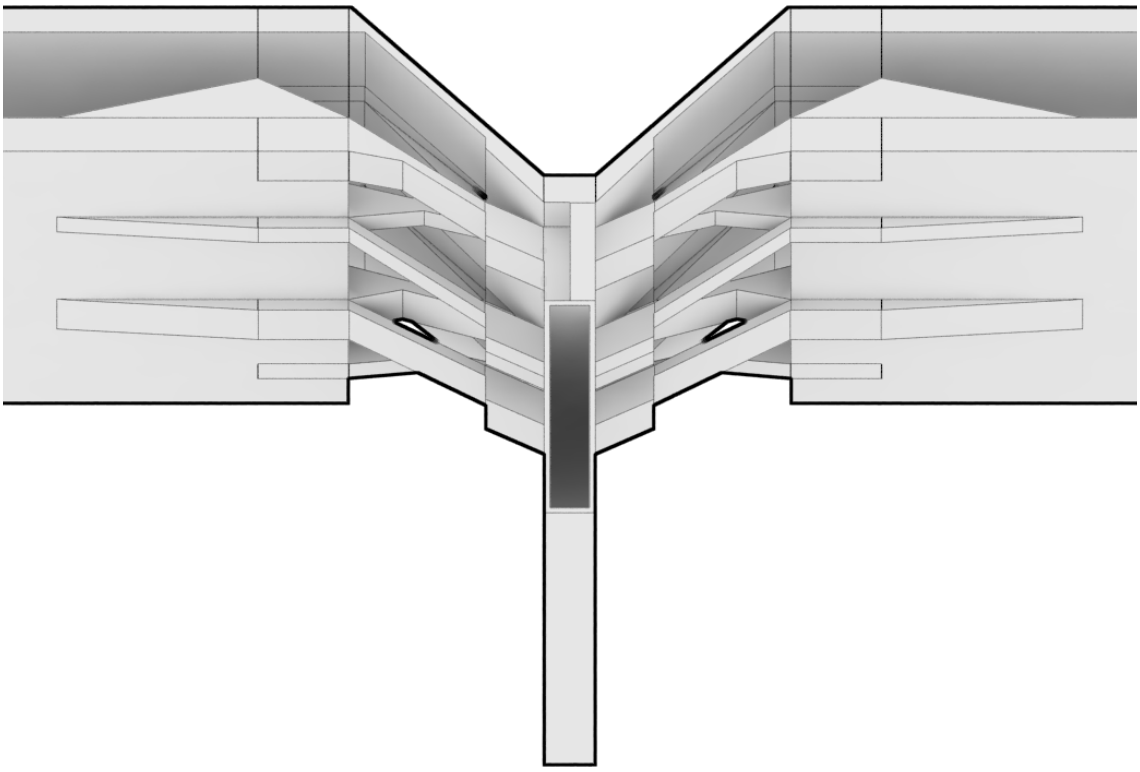

Figure 52: Detail View of the Material Blending Mould, showing intedigitation and shallow attachment angle characteristics.

ticated reciprocity between material and form found in the enthesis would function equally well here[57], 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 due to the fact that 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[58].

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57 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.

58 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.

3.3.6. Thesis Design Methodology- Workflow Sequencing

In fact, this also raises a point concerning the 'steps' of the proposed workflow, in the first 'stage' of which the dimensional and material parameters of the existing interface have been used as a starting point for the design process. As it will be explained in the following chapter, however, an alternative take to this would be to conduct the process from a material-first starting point. This would entail starting off with an identification of appropriate and 'verified' multi-materials that could be suitable for potential use in the new envelope, an analysis of their structural and behavioural properties and a definition of the mould's formal attributes based on these properties. The limitations posed by the aforementioned inaccessibility of the scarce information on graded materials and the fact that any structural analysis on these is a highly sophisticated and non-mainstream enterprise performed by specialised engineers, meant that in this case this approach was not followed. Being able to reverse the 'steps', however, illustrates further the inextricability of matter and form in the design process, which is something that will be fully expanded upon in what follows.

3.3.7. 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.

3.3.7.1. 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[59]. According to Bleakley (2016), the results show that the maximum stress (Figure 53) and displacement (Figure 54) occur in the middle of the outer glass pane of a double-glazed unit, "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.* 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.

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59 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.

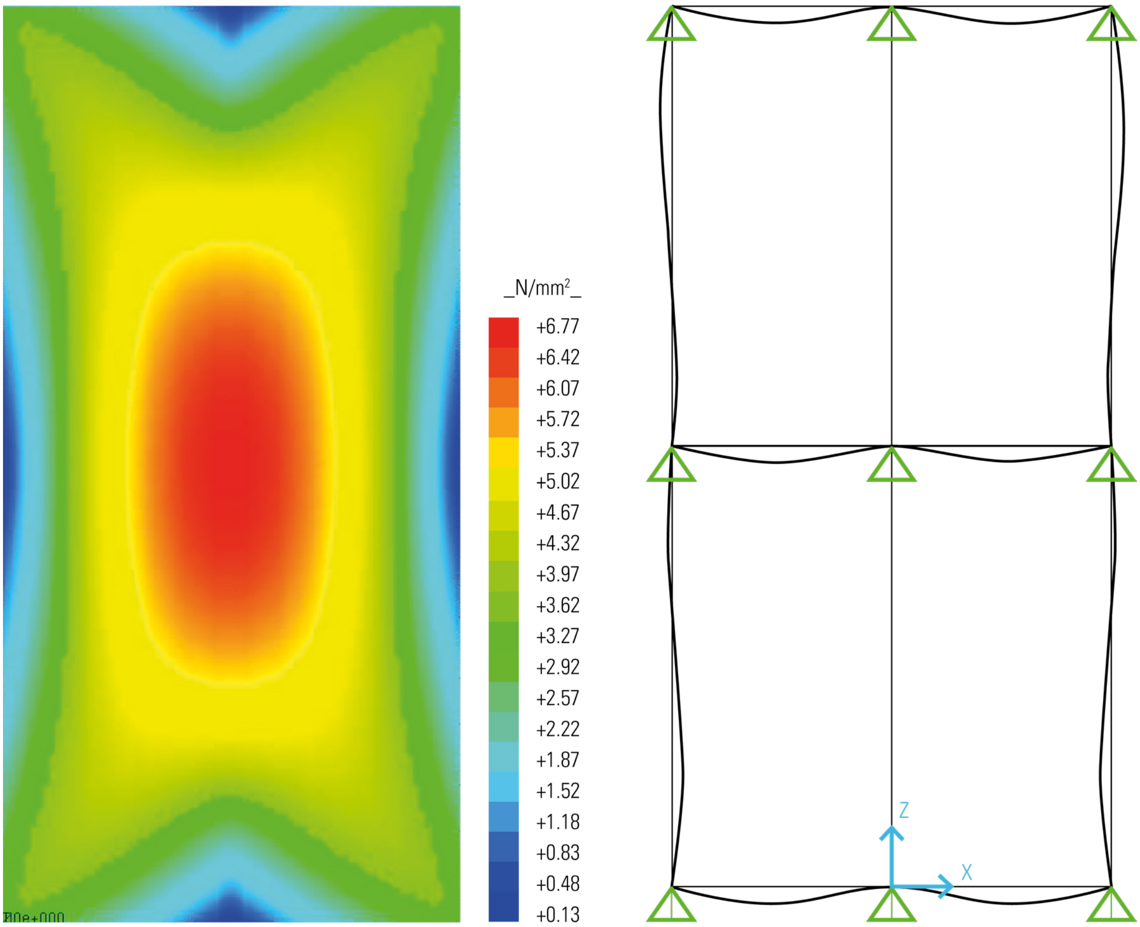

Figure 53: Stress Analysis of a Curtain Wall Glazing Unit, showing stress distribution on the glass (left) and on the frame (right).

3.3.7.2. FGM Manufacturing Techniques

Regarding the existing FGM manufacturing techniques, as it has previously been examined, the main ones include centrifugal powder forming and gravity sedimentation among others. As far the mould configuration is concerned, there are several sub compartments[60] placed vertically within the master mould that contain the materials to be fused over the course of the simulation. As the aim is for these to be blended crosswise across the vertical mould, a centrifugal force has been deemed appropriate to achieve this.

3.3.8. 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

60 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 connection).

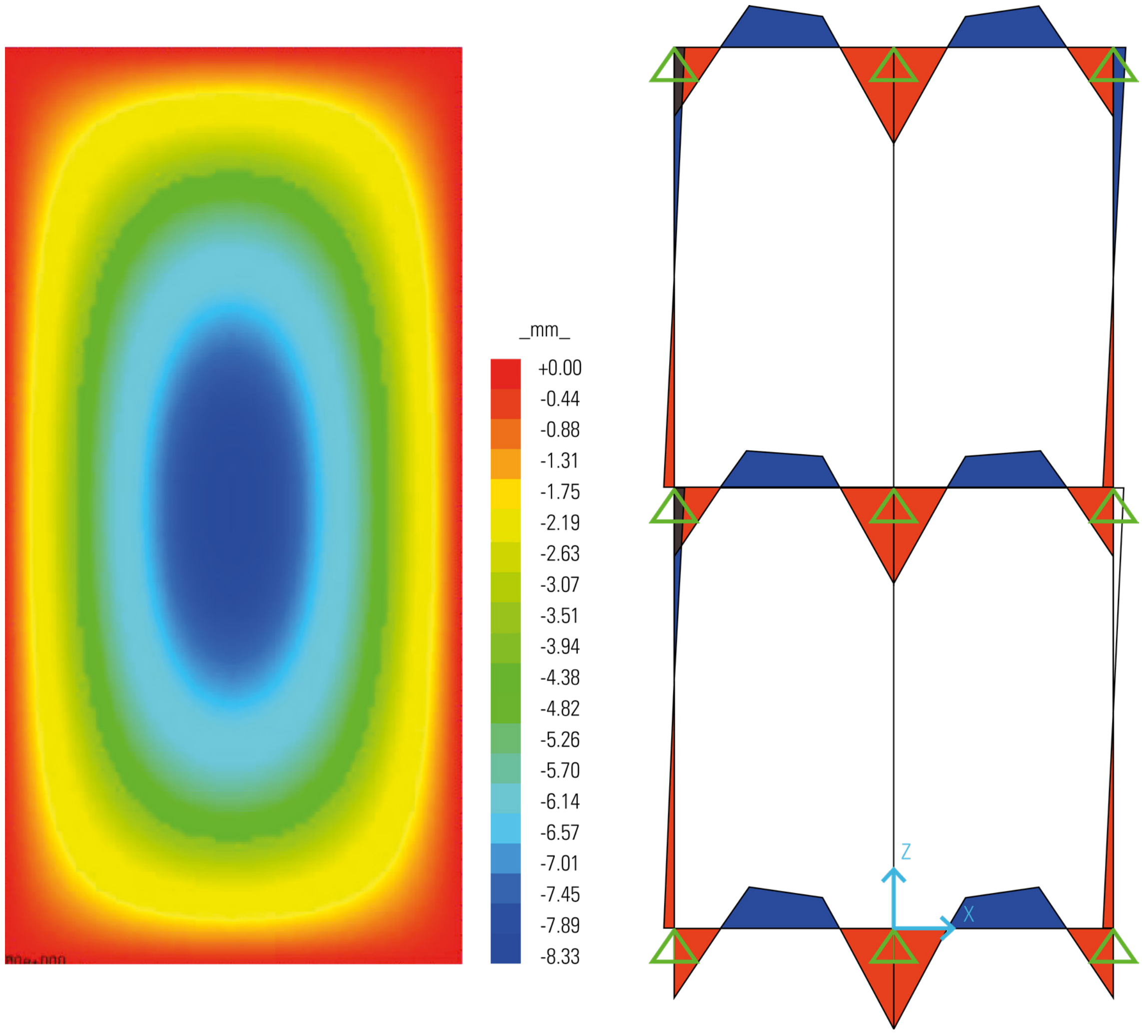

Figure 54: Displacement Analysis of a Curtain Wall Glazing Unit, showing deflection distribution on the glass (left) and anticipated deflections on frame members (right).

the container. The blending in this case reached the required formation[61] after approximately ten seconds and eventually terminated at twelve.

3.3.9. Main Blend- Evaluation & Critique

Strikingly, and 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 (Figures 55 & 56). 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.

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61 This criterion determining the interspersed patterning of the neighbouring materials in the fused regions is visually verified and explicitly presented in 4.3.7.10.

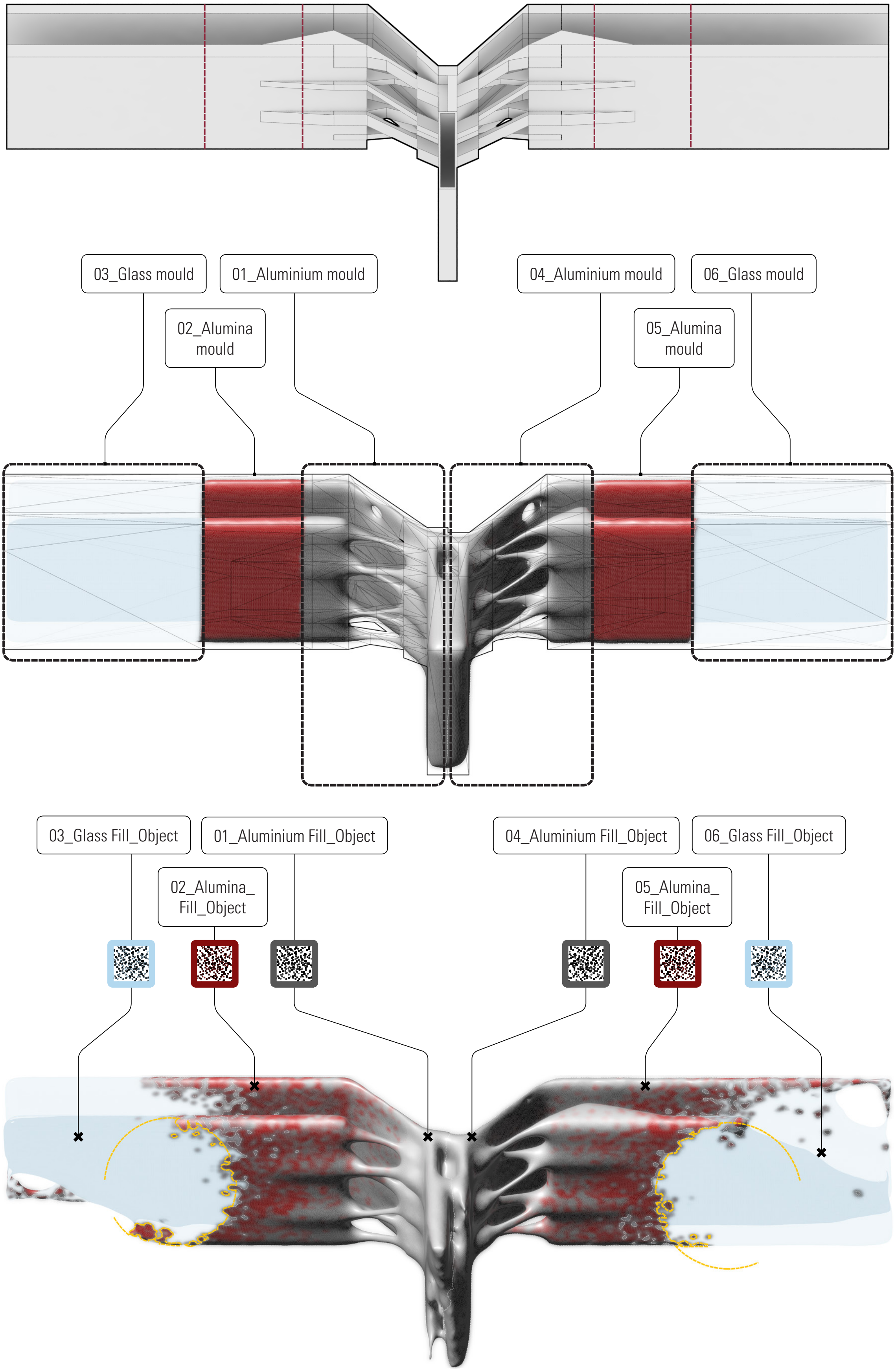

Figure 55: The Various Stages of the Blending Simulation. Shown from top to bottom are the mould (indicating the sub-compartments for aluminium, glass, and alumina), the liquid materials at the first second of the simulation in the middle, and the final blending distribution at the twelfth second at the bottom. The orange circles indicate the circular arrangement of the aluminium and alumina that match the loading pattern.

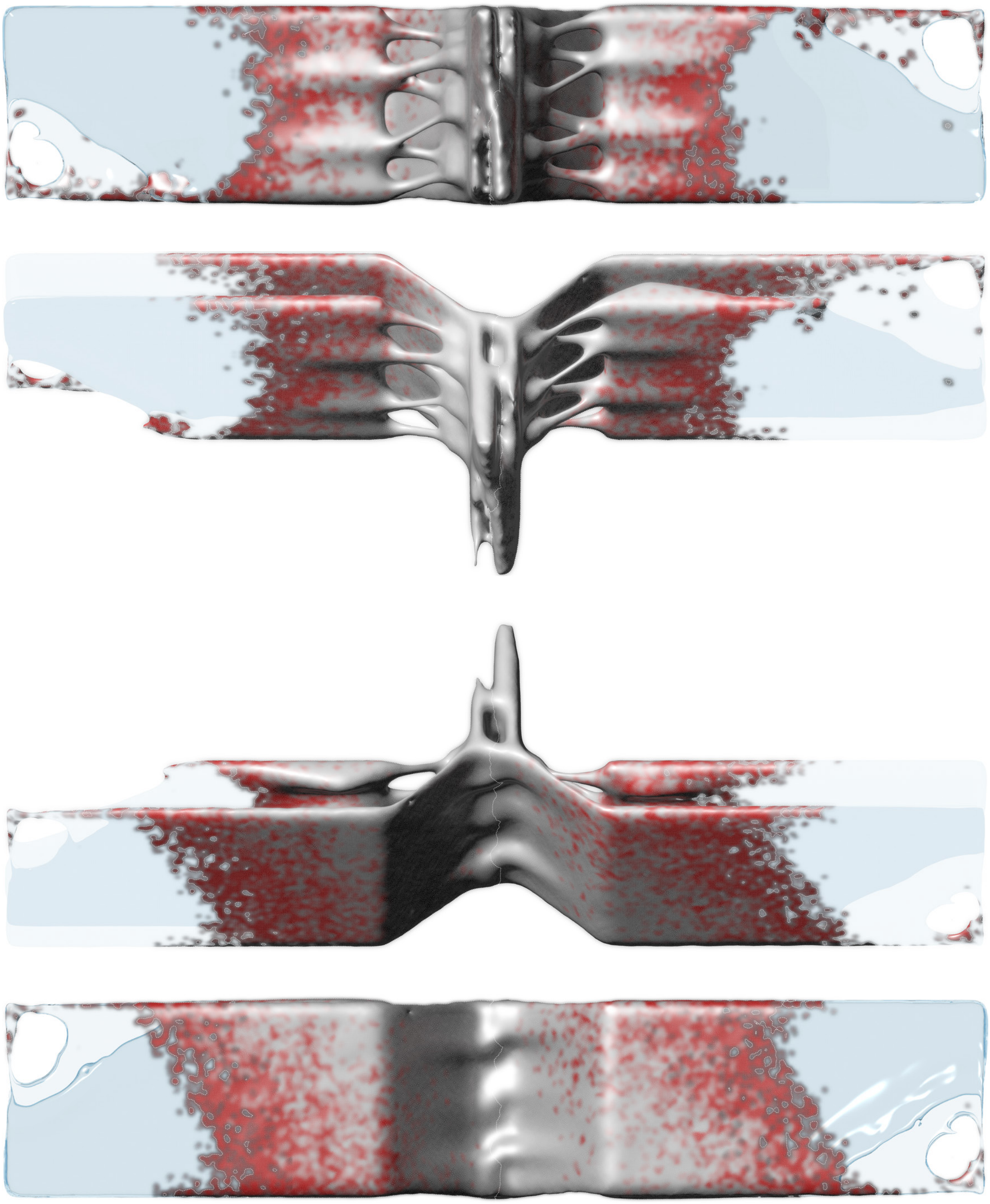

Figure 56: Internal & External Views of the Multi-Material Glass to Aluminium Frame Redesign.

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.

04

THINKING WITH BLENDS

4.1. CAD Literature Review- Part II

4.1.1. A Materially- Based Origin

Expanding on the discussion in 1.8.2., and going back to the commercial 3D CAD software used by architects today (introduced in 2.2.1.), these have their origin in the advertising, entertainment, transportation and military industries. As a result, "there are fundamental aspects of digital modelling software more deeply connected to the geometric mediations of automotive, airplane, and shipbuilding traditions than to architecture" (Young, 2013, p.122). Additionally, many of the primary operations performed in these disciplines relate predominantly to questions of continuity. The importance of preserving the seamlessness between surfaces that make up the different segments of a boat or car for instance, is a key aspect in naval and automotive design as it ensures the adequate performance and dynamic behaviour of a vessel within a body of water or air. "In order to describe and design these surfaces, shipbuilders developed a process that negotiates drawn geometry (lofting), material experimentation (splines and sweeps), and sensory aesthetic judgement (fairing)" (Young, 2013, p.125). Consequently, and as it will be described more extensively, in this process of formal description geometry and materiality used to be intrinsically linked together and informed one another reciprocally. Even more strikingly and appropriately for the context of the thesis, what then ended up in the 1950s as the first CAD commands of lofting and sweeping (utilised to describe digital geometry and form), as well as CAD elements like control point curves and splines all had a materially-based origin.

The control points that describe a curve for instance, were based on the original use of so-called ducks (named because of their shape resembling a duck) that were essentially lead-weights employed to preserve the shape of a metal, plastic or wooden spline curve (Figure 57). These curves in their turn were utilised in lofting, which was a ship-building practice initially developed in the seventh century in the Mediterranean when builders shifted to the practice of constructing a boat from a series of frames that were clad to make a hull, as opposed to a hull-first construction (Figure 58). As a result, the CAD spline of today is essentially based on the prior existence of "a [physical] material line [that was] using the properties of bending in the material and moments of force constraining the spline into various configurations" (Young, 2013, p.126). Additionally, another more immediate way of studying form and of constructing doubly curved surface templates by the shipbuilders of the time, was to employ sand or clay moulds and use guide-rails in order to imprint the desired 3D shapes in the underlying material medium.

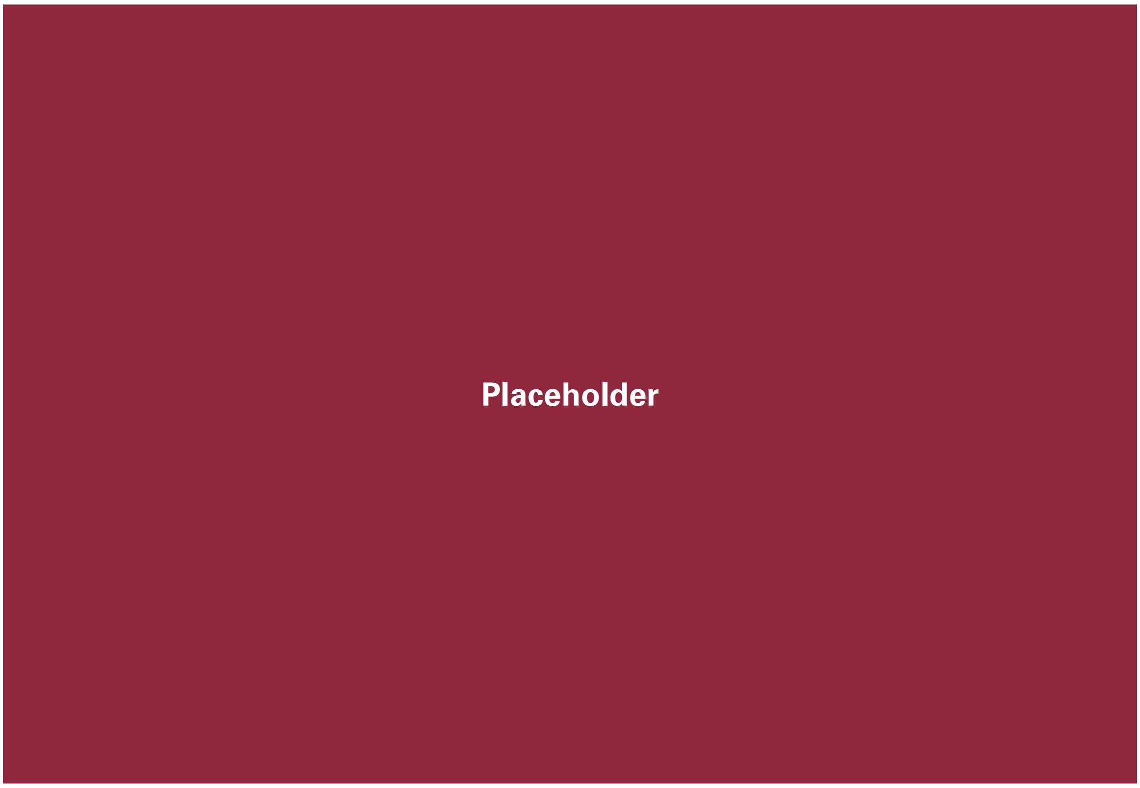

Figure 57: A Series of Lead Ducks, constraining a wooden spline to shape.

Placeholder

Figure 58: Drawing of a Boat Hull, showing the position of the ribs that will make up the structure of the boat that will eventually be clad.

4.1.2. Material- Less Computer Elements

It was in the mid-20th century that every part in the vehicle production chain started becoming very detailed and precise, which is something that necessitated an equal precision in the forms and geometric descriptions of the vessels that contained these parts. Paul De Casteljau and Pierre Bézier, eventually came up with the corresponding algorithms and digital curve definitions for performing all of the above operations in a digital environment. However, it is rather clear from the above that beyond the complex science behind these transcriptions and according to the materially-anchored conceptual blending theory (Hutchins, 2005) that will be described in detail in the following chapter, Bézier was essentially using the material anchor of the lead-weight constrained wooden spline as a grounding mechanism for projecting and substantiating abstract mathematical concepts and ideas. What started off as a materially grounded translation, however, generated a series of material-less computer elements, which when pieced together resulted in the boundary representations described in subchapter 2.2.1., today's ubiquitous element for designing form digitally. These initial "affordances of material reality" (Malafouris, 2013, p.66) that were fundamental and intrinsic to form generation were effectively discarded and became replaced by empty containers synonymous to a hylomorphic understanding of design, which is something that also coincided in time with the dualist ontology so prevalent during modernism and the twentieth century.

4.1.3. Cartesian Matter

Apart from the Aristotelian origin of this duality that was touched upon in the thesis introduction, the modern traces of hylomorphism go back to the time of Descartes, "who defined matter in the seventeenth century as corporeal substance constituted of length, breadth, and thickness; as extended, uniform, and inert" (Coole and Frost, 2010, p.7). This effectively meant that matter in general was something thought to be measurable, quantifiable and effectively subordinated under a linear logic of cause and effect. Furthermore, this envisaged ability in the seventeenth century to calculate the natural world and effectively to claim mastery over it went hand in hand with the definition of the mind and "the cogito (I think) … as ontologically other than matter" (Coole and Frost, 2010, p.8). Interestingly, this ontological separation found a fertile ground in nineteenth century industrial practices in which the invention of new types of materials that were malleable (including plastics, synthetic rubber etc.) promised "liberation from manual labour" (Drazin and Küchler, 2015, p.270). Together with:

> "the capacity for machinic transformation, [this] led to the separation both conceptually and concretely of the design of an object, its form and function, from its material, which in turn became secondary and passive in relation to the chosen form. Design itself, in turn, now was no longer thought to have an inherent materiality and could be transferred to many different materials." (Drazin and Küchler, 2015, p.270)

4.1.4. Homogenisation & Multiple Realizability

Additionally, this taking over of mechanised mass fabrication and liberation from labour, apart from separating design and material also had an impact on the actual composition of the materials that various objects and structures were made of. James E. Gordon (1988, p.135) suggests that for example:

> "steel, especially mild steel, might euphemistically be described as a material that facilitates the dilution of skills. Manufacturing processes can be broken down into many separate stages, each requiring a minimum of skill or intelligence… At a higher mental level, the design process becomes a good deal easier and more foolproof by the use of a ductile, isotropic, and practically uniform material with which there is already a great deal of accumulated experience. The design of many components, such as gear wheels, can be reduced to a routine that can be looked up in handbooks."

As a result of all these developments taking place in adjacent disciplines, and similarly to the practice of using lineaments touched upon in subchapter 3.2.3., the aforementioned spline and lofted surface that solely describe exteriority, formed the main CAD elements of a dualist design thinking that was biased towards the limited definition of either solidity or emptiness. Nowadays, "this idea of design as both preceding and independent of the material within which it is taking on form has given way to new technical ways of creating form so that today prototypes may exist virtually on a computer, to be materialized in many different materials"[62] (Drazin and

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62 Akin to multiple realizability in AI, the thesis that a single mental state can be realised by

Küchler, 2015, p.271). Additionally, when discussing about this somewhat disengaged relation between thought and material, Lambros Malafouris (2013, p.6) states that:

> "most of the grounding assumptions that define what we know about the human mind, but also the ways by which we have come to know what we know about the human mind, have been premised and nurtured in the absence of materiality. Perhaps a look at the history of Western thought can teach us that the study of nous always favoured the order of Platonic essences and ideas over the messiness and fluidity of pre-Socratic becoming."

4.2. Conceptual Blending

4.2.1. Theoretical Objective

Going back to the CAD software discussion, it becomes apparent that there is a peculiar resonance of past, gone by, materially-related practices in the CAD commands of today that a designer is somewhat unaware of. This is even more so due to the fact that these commands have ended up being mere form-generation tools that cannot incorporate content. The intent in the ensuing chapter, however, is to re-establish this lost connection of materiality to the hollow form containers that result from the application of these tools, albeit not so much on a deep algorithmic and performative level but rather in the mental space that one constructs when designing with them and in the context of a multi-material design workflow. In addition, going back to the Cartesian conception of mind and matter:

> "it seems that the purification project of modernity (Latour 1993) that habituated our minds to think and talk in terms of clean divisions and fixed categories makes it very difficult to shift the focus away from the isolated internal mind and the demarcated external material world and toward their mutual constitution as an inseparable analytic unit." (Malafouris, 2013, p.16)

This is a condition that the following will attempt to overcome by demonstrating that when the so-called 'internal' thinking process is examined during a multi-material design workflow, this demarcation simply does not exist and is superseded by a much more 'messy', conceptually nested, and blurred relation between geometry and material.

More specifically, the main objective in the proposed multi-material design workflow will be to answer the question of whether the containing mould for blending materials within, is merely and purely a mental construct that is disconnected from the external world. This deeply entrenched idea, still prevalent today, is not different to what Vasari praised half a millennium ago by suggesting that "the greatest geniuses sometimes accomplish more when they work less, since they are searching for inventions in their minds, and forming those perfect ideas

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many different kinds has now been discredited in favour of the non-reductive physicalism idea.

which their hands then express and reproduce from what they previously conceived with their intellect" (Gürsoy, 2016, p.854). The response to this hylomorphic belief that is based on an intuitive, almost esoteric emergence of an idea of form will be to initially show that the vessel is effectively designed through a process where form emerges from a considered awareness of physical reality. This reality consists of existing, similarly-scaled and functioning material references that are combined to construct a novel multi-material artefact.

4.2.2. Material Data & B-Rep Merging

On that construal, the main claim is that in the proposed design methodology b-rep creation and manipulation does not take place through a process in which the designer outputs a form that pre-exists in the mind autonomously, but is informed by material parameters that are external to one's mind per se. It effectively allows one to use parts of various collected material data and merge them together with and onto a b-rep, which as discussed is typically and conventionally perceived as a hollow material-less object. This is done through *conceptual blending* (Fauconnier and Turner 1998, 2002). Rather than being a straightforward overlapping of different elements, however, the blending takes place in a nested manner abiding to the principle that "the existence of a good blend can make possible the development of a better blend" (Fauconnier and Turner, 2002, p.24). But before proceeding further one ought to explain what conceptual blending actually is.

4.2.3. Conceptual Blending Theory- Definition & Thesis Relevance

According to the proponents of the theory, "conceptual integration— "blending"—is a general cognitive operation on a par with analogy, recursion, mental modelling, conceptual categorization, and framing" (Fauconnier and Turner, 1998, p.133). It is a unique characteristic of the human mind that instigates the vast complexity of thoughts and conceptual constructs that emerge from and within it. Gilles Fauconnier and Mark Turner (2002) moreover discuss the fact that it is a mechanism that has remained largely unexplored in cognitive theory, while arguing that understanding and describing it can lead to novel insights into how the human mind operates. One can then ask at this point why is conceptual blending theory relevant to the thesis topic and how does it relate to the main argument. The initial response to this is that new forms of materiality (in this case multi-materiality) are necessitating a reconsideration of the tools that an architect designs with, as well as a re-examination of the design process itself. As this process is to a very large extent mentally related, thinking about form, space and material in their virtual, as well as physical states is something that also needs to be looked into from a new perspective. As aforementioned, in the context of a contemporary material reality that has acquired a reconsidered importance in the design field and more broadly in its engagement and influence on the human mind, clean categories and divisions are to be rethought. Conceptual blending theory is therefore an appropriate means of analysing this gradual (re-)seeping of materiality in contemporary CAD procedures, allowing one to describe and structure the thought processes behind them and effectively argue for an *informed and networked engagement of mind and* *matter* in the design process. As an argument, this is more broadly related to the wider theoretical and technological elevation of the importance of matter and materials, which is currently taking place in architecture, design and beyond, in the early 21st century[63].

4.2.4. Blend Running

Carrying on, the basic idea behind blending theory it is that there are a number of different mental constructs such as word and sentence meanings, metaphors, argumentations etc., which were previously thought to be separate and disconnected from one another. The theory then proposes that there are projections that link these "related linguistic [or not] constructions. [These, connect] one viewpoint to another and [set] up new viewpoints partly on the basis of old" (Fauconnier and Turner, 1998, p.134). This effectively is a process that "typically involve[s] conceptual integration" (Fauconnier and Turner, 1998, p.134). Additionally, it is argued that it is "an established and fundamental finding of cognitive science that structure mapping and metaphorical projection play a central role in the construction of reasoning and meaning" (Fauconnier and Turner, 1998, p.135). Strikingly, there is also a very close metaphoric (or conceptually blended) similarity of the theory to the proposed multi-material simulation methodology. When referring to how these constructed blended spaces can be elaborated on, Fauconnier and Turner (1998, p.175) state that this takes place through a process of mental simulation, otherwise known as "running the blend."

4.2.5. Conceptual Blending Model- Structure

Moving into the particularities of the process, a blending model or network typically consists of four connected mental spaces, each feeding into the other to generate the blend. The first of the networks in the sequence of design operations in this case, consists of two spaces on either end of it, namely a generic and a blend space. The generic space provides the abstract structure common to the input spaces, linked together by "a cross-space mapping of elements and relations" (Wang, 2013, p.110), and followed by "a selective projection from two [in this case and as it will be seen later on, four] inputs into the blend" (Wang, 2013, p.110) (Figure 59).

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63 This reconsideration of materiality was touched upon in subchapter 1.8. Additionally, according to DeLanda (1995), the homogenization of materials and the conversion of their behaviour into routine processes, shifted the attention of philosophical discourse to questions of living processes (vitalism), symbols and texts among others. Today, however, "thanks in part to the new theories of self-organisation that have revealed the potential complexity of behaviour of even the humbler forms of matter-energy, we are beginning to recover a certain philosophical respect for the inherent morphogenetic potential of all materials."

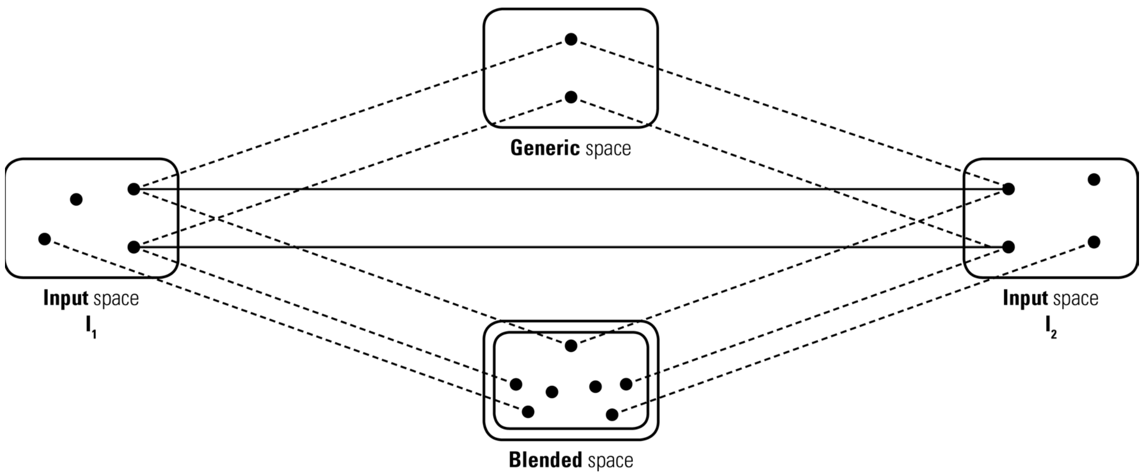

Figure 59: Structure of a Standard Conceptual Integration Network, consisting of generic, two input, and a blended space.

4.2.6. Design Workflow Conceptual Spaces

More specifically, in this case the abstract, generic field consists of the general terms of connective element, succeeded by other parameters, which are fundamental to the design task such as materiality, form, characteristics and function. The first of the input spaces is populated with the terms that make up a cladding mullion connection (discrete materials, orthogonal form, vertical orientation, partial transparency and opacity, waterproofing etc.) and the second one with terms relating to the enthesis (multi-material, linear and inter-digitised formal and material arrangement, opacity, enabling kinetic functionality etc.). As per the principles of conceptual blending, the input space of the latter corresponds only partially to the space of the mullion connection, with the commensurate links being termed “counterpart connections” (Fauconnier and Turner, 1998, p.137). This partial symmetry means that the two spaces can afford adequate outputs towards a coherent blend without the outcome being merely a composition of the two; something which is akin to “biological evolution [and] not chemical composition” (Fauconnier and Turner, 1998, p.136). The outcome is a blended space consisting of terms such as cladding mullion connection, multi-material, orthogonality and partial linear or branching arrangement, transparency and opacity, waterproofing etc.

4.2.7. Conceptual Blending Theory- Integration Network Types

In general, conceptual integration networks can be separated into different types: simplex, mirror, single-scope and double-scope mapping, ordered in sequence from ones that are simple to ones that are more complex and elaborate. Correspondingly, in terms of type, the process effectively generates an integration network that is single-scope, “because the organizing frames of the inputs are different; the typology of [cladding mullion connection] projected into the blend is exclusively from input space 1” (Wang, 2013, p.113).

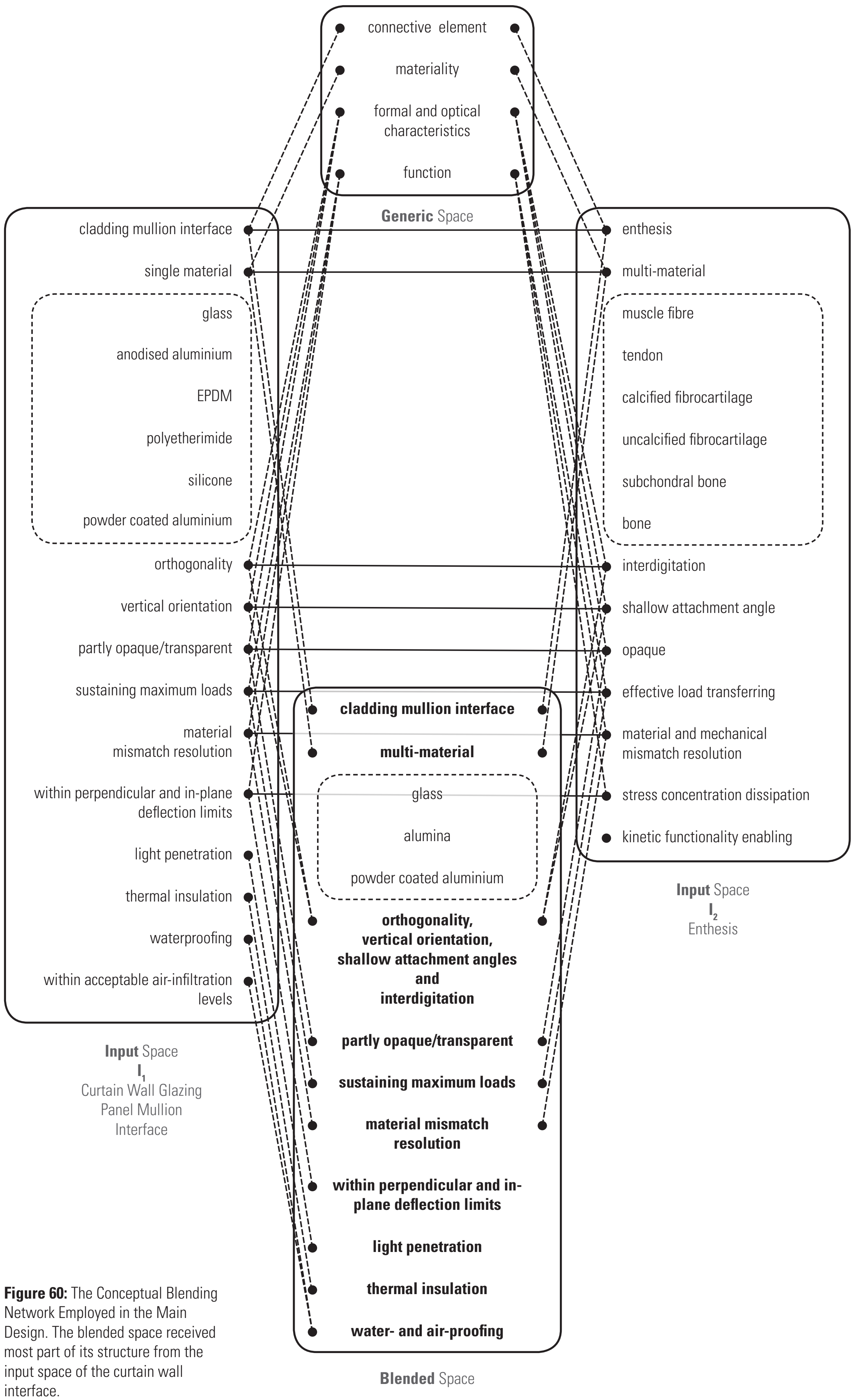

Figure 60: The Conceptual Blending Network Employed in the Main Design. The blended space received most part of its structure from the input space of the curtain wall interface.

4.2.8. Conceptual Blending Theory- Integration Network Types

Before proceeding further, there is a further elaboration that needs to take place in regards to the fused space. This relates to the fact that blending in this case concerns a design process, which has a physical output as opposed to an operation that only takes place conceptually or is merely metaphorical. The standard integrative network result has to therefore be investigated for inconsistencies and potentially one or more new input spaces added to it. This happens because each of the broader terms within the two input spaces contain subgroups subsumed under each 'category'. This is necessary for the resulting space to have the detail needed in order to inform a design operation. The multi-material and discrete material groups are therefore broken down in muscle fibre, tendon, fibrocartilage, calcified fibrocartilage and bone tissue, and powder coated and anodized aluminium, silicone, EPDM polytherimide, and glass respectively. As mentioned, the type of integrative network is single-scope and therefore the blended space receives input from the material space of the cladding mullion detail, which, however, according to blending theory is selective. As presented in 3.3.3., aluminium, and glass are the main elements of the facade system, one providing structural support and the other transparency and all other mediating discrete material parts are removed from the selection as they do not allow for the formation of a functionally graded material. The inconsistency here is that as research has shown, these two materials do not exhibit fusion compatibility. In response to this, a third and fourth input space are added to the network that provide the necessary bridging substances to allow for a glass-aluminium multi-material. As discussed in subchapter 3.3.3., glass can be fused with polycrystalline alumina and alumina in its turn with aluminium. Alumina is therefore a third material that can be added to the blended space. This can capacitate the blending of glass and aluminium allowing them to be placed under the term 'multi-material' (Figures 60, 61 & 62).

4.2.9. Conceptual Blending Evaluation

Subsequently, when analysing this against the main operations that characterise conceptual blending, composition, completion and elaboration (Fauconnier and Turner, 2002) can all be discerned in the process. In regards to composition: "Blending composes elements from the input spaces, providing relations that do not exist in the separate inputs… Fusion is one kind of composition. Counterparts can be brought into the blend as separate elements [cladding mullion connection, multi-material, partial transparency and opacity, waterproofing] or as a fused element [orthogonality together with partial linear or inter-digitised arrangement]" (Fauconnier and Turner, 1998, p.144). In terms of completion:

> "We rarely realize the extent of background knowledge and structure that we bring into a blend unconsciously. Blends recruit great ranges of such background meaning. Pattern completion is the most basic kind of recruitment: We see some parts of a familiar frame of meaning, and much more of the frame is recruited silently but effectively to the blend." (Fauconnier and Turner, 2002, p.48)

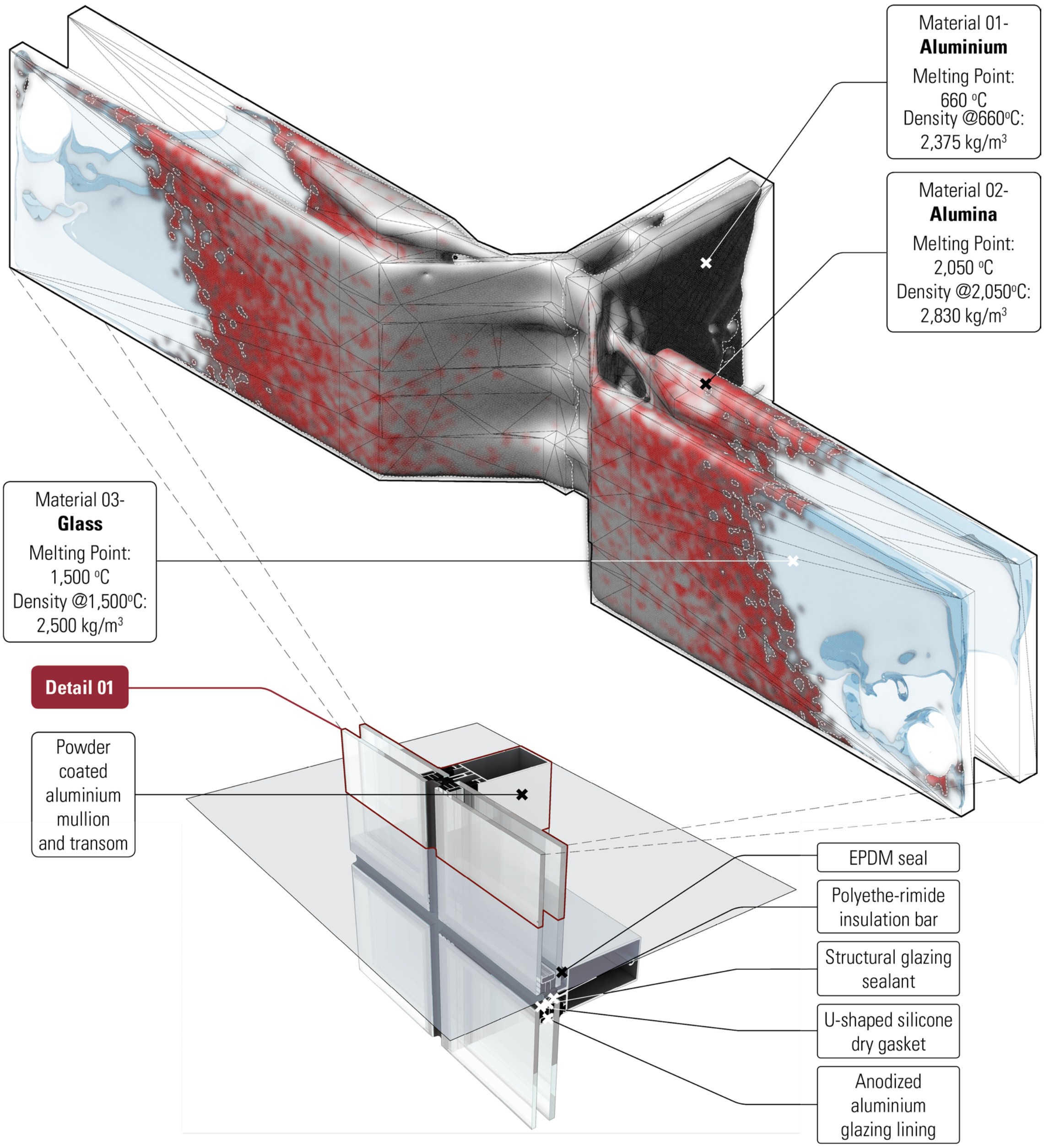

Figure 61: Exterior View of the Multi-Material Mullion Interface, showing its relation to the original curtain wall glazing segment.

In this case, it is quite obvious that the familiar notions of inside and outside, verticality and horizontality, building facade and perhaps even 3D printing as a general notion contribute to filling in the mental puzzle in order to make sense of the blend. Lastly, as far as elaboration is concerned, as the emergent structure of the blended space becomes clearer there is a series of questions that become available that could allow for a more comprehensive understanding of the blend. The larger group of linear/inter-digitised form contains terms such as multiple attachment sites and shallow attachment angles that are both very effective mechanisms for load dissipation in the enthesis, discussed previously in subchapter 3.3.4.3. In addition, orthogonality was another principle preserved in the blend, which consisted of the standard vertical plane of separation between inside and outside in a building facade. The question that arose in this

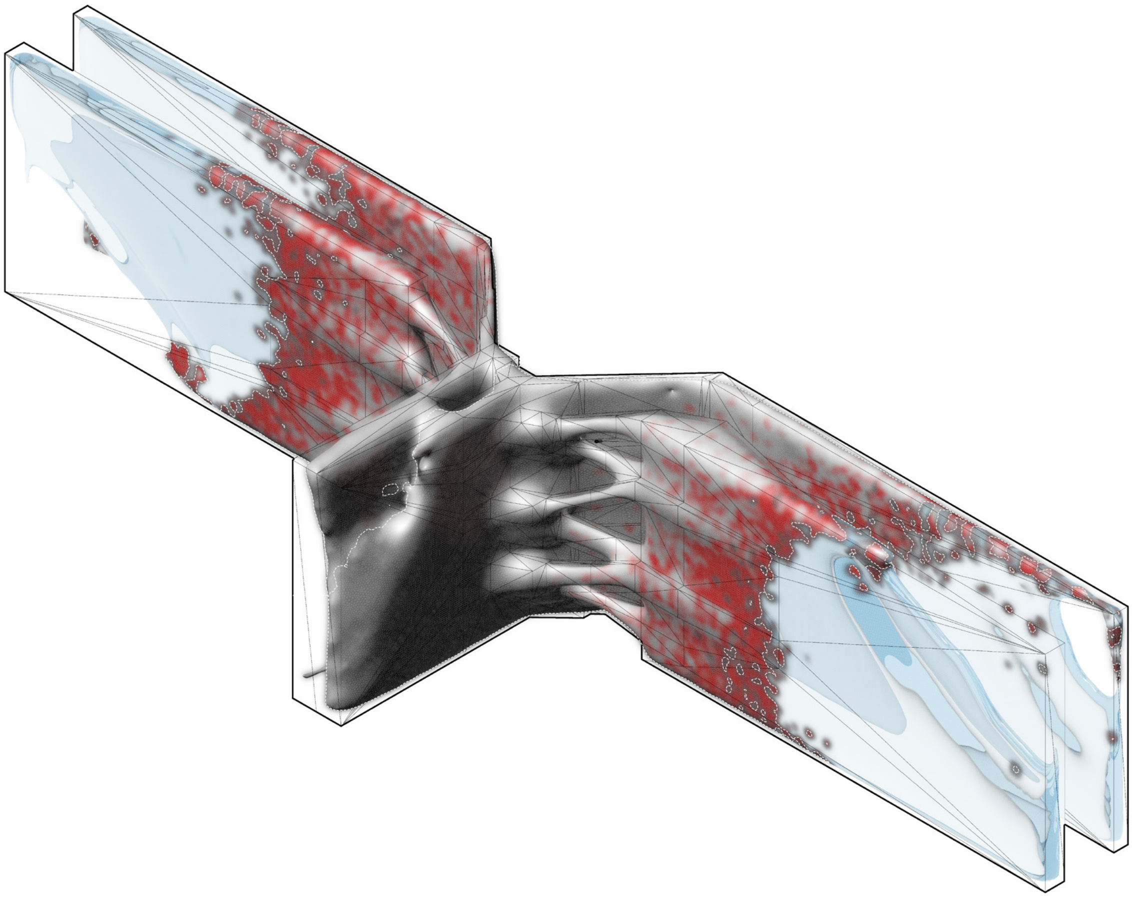

Figure 62: Internal View of the Multi-Material Mullion Interface.

instance that was answered partly also in 3.3.4.3., is where would inter-digitation occur in the vertical plane of the aluminium-alumina-glass multi-material.

In effect, the ensuing integrated space consists of a pool of ingredients that exist on a conceptual level and that can be fed into the development of a better blend as aforementioned, which in this case is a form generation procedure. A further elaboration that follows up on the one before, is how can one design with these notional tools in mind. This in turn leads nicely to a description of the design process that takes place in the CAD environment, which to the contrary to what one might think is similarly generated through a conceptual blending operation.

4.2.10. Materially Anchored Conceptual Blending

Moving forward, when using this mentally constructed toolset to carve out a form with, the conceptual integration that one forges is of a slightly different kind. This is namely related to Edwin Hutchins's (2005) addition to conceptual blending theory, termed *materially-anchored conceptual blending*. "What essentially happens in those cases, put in very simple terms, is that the vague structure of a flexible and inherently meaningless conceptual process (e.g., counting), by being integrated via projection with some stable material structure or things, is transformed into a perceptual or physical process" (Malafouris, 2013, p.105). The author describes the principle by providing a simple example of the mental formation of a queue of people in line to purchase theatre tickets. In order for the mind to perceive the people queuing in sequential order, "the gestalt principle of linearity makes the line configuration perceptually salient. Our perceptual systems have a natural bias to find line-like structure" (Hutchins, 2005, p.1559). But a line in the first instance is not necessarily a queue. For it to become "a queue, one must project conceptual structure onto the line. The conceptual structure is the notion of sequential order" (Hutchins, 2005, p.1559). This conceptual structure is called the trajector, which effectively is a form of notional vector superimposed on the line of people in order to give it order and sequence (Figure 63). Satisfying the principle of two input spaces feeding into an emergent perceptual blend, "phenomenologically, the object that emerges from the blending process, that is the queue, is experienced in the perception of the material structure" (Hutchins, 2005, p.1559).

Figure 63: The Formation of a Queue Mentally, requires according to Hutchins (2005) conceptual blending to occur unconsciously in order to perceive the sequence of people linearly and directionaly.

At this point, there is a brief discussion of whether the line of people is first perceived by the mind and then conceptually represented or whether there is even the need to separate the two as opposed to the perceptual process being directly a conceptual one. The author argues for the latter and effectively proposes that one of the two conventional input spaces that are mental is replaced here by one that is material. This acts as an anchor for projecting conceptual elements on, while the subsequent combination of the two spaces gives rise to an emergent blend. More interestingly:

> "It might be better to ask under what conditions something becomes a material anchor than to ask whether it is a material anchor. If conceptual elements are mapped onto a material pattern in such a way that the perceived relationships among the material elements are taken as proxies (consciously or unconsciously) for relationships among conceptual elements, then the material pattern is acting as a material anchor." (Hutchins, 2005, p.1562)

4.3. Main Thesis

4.3.1. Materially Projected Boundary Representations

The question then becomes how materially-anchored blend theory is applied to the design of the multi-material curtain wall detail. In this case, the roles of each of the elements that feed into this blending operation are slightly reversed. As mentioned, the manipulation of (seemingly) material-less b-reps is the main way of designing in commercial CAD software. Designing with non-material entities is something that the design thesis is fundamentally against, with the use of material-information-loaded particle system elements being a response to this. Part of the workflow, however, is the generation of digital containers for materials to be poured within and unavoidably one has to resort in b-rep manipulations to achieve that. The point to be proven here, however, is that although working with material-less entities, through the aforementioned blending theory one is in fact projecting material structure on them. In this case, the three principles of composition, completion, and elaboration have to be slightly readjusted in terms of what comes before and after. Initially having a b-rep object in the CAD environment, itself the result of a blending operation, one starts where this first blending finished off. In the queue example, in order to complete the blend, Hutchins was proposing that: "Other elements are recruited so that seeing the queue 'makes sense' in the cultural context of people seeking a service and the (far from universal) cultural principle of "first-come, first-served"" (Hutchins, 2005, p.1559). Following up, the b-rep in this case makes sense in the wider context of being used as a mixing vessel within which material fusion will occur eventually. This in turn necessitates the creation of compartments that will contain the individual sub-materials that will blend together. This effectively means that when one is looking at the b-rep one has to firstly think in broader material terms, secondly in terms of sub-materials and thirdly in terms of sub-divisions that will contain these sub-materials. In this case, what Hutchins termed a materially-anchored conceptual blend becomes a *b-rep-anchored notional material blend*. How the two correspond with one another is that the input space of the line of people, which is physically material is now replaced by the input space of the boundary-representation, which although being a virtual entity is perceived and conceived visually in a direct manner, to the point of being understood as physical. The conceptually created trajector that was then projected on the line is now replaced by the materials that will be blended at the next stage, which however exist conceptually and not as directly perceived entities. In simple terms one is looking into a b-rep and projecting material information on it. In a more elaborate understanding of this process, the virtually material-less but directly perceived and as a result physical (but non-material) b-rep, forms an anchor onto which materials which are not physical but exist mentally are input, in order to give emergence to a perceptually blended space in which one is working with a material-less entity but thinking and designing into and with it, with materials (that have been generated through a conceptual blend) in mind. Previously, the result of the blend was simply the formation of a queue mentally, in this case it is a *materially projected boundary representation*.

4.3.2. Conceptual Materiality

A point of clarification is that materiality here is not a tactile condition, but exists conceptually and is manipulated through computer objects, which, however, are perceived directly and therefore can be said to be understood in one's mind as physical. This is equivalent to the example of a photograph of a person that one is acquainted with, which although being in reality a series of colours on paper that have nothing to do with a real face, one's mind perceives a person through them. For this construction of identity to be made between the familiar face and its representation, there are a number of staggeringly complex mental operations involved that evolution of the human brain took thousands of years to develop (Fauconnier and Turner, 2002). Correspondingly, these complex series of processes are behind the b-rep being perceived as a "real" (in the physical sense) object, while the existence of these allows one to eschew consciously thinking and questioning its virtual or physical status. Here, one can also ask in what form are the materials to be projected onto the b-rep stored in one's mind. If one begins to be conscious of the corresponding thought process, it then becomes evident that there is a certain amount of data about the materials that is removed from the equation and only information (such as colour and function) that contributes to the design task preserved. This effectively relates to one's background and degree of knowledge about the substances involved, which would of course differ from a material scientist to a designer and to an artist, as well as the nature of the material operation (whether of scientific, creative, or of another scope). Consequently, the aforementioned mental material projection is something akin to augmented reality, or what David Kirsh describes when discussing cognitive projections as "a way of 'seeing' something extra in the thing present (…) a way of augmenting the observed thing, of projecting onto it" (Kirsch, 2009, p.2310).

4.3.3. B-Rep Anchor Hypothesis Verification

Moving forward, further elaboration means that the materials need to be three, ordered from one that is structural (aluminium) in the centre, with alumina bridging the glazed areas on either side of the central spine, all notionally projected on the b-rep anchor and all having corresponding b-rep sub-compartments built for them. The aforementioned, sub-group principles of inter-digitation and multiple attachment sites take place between the aluminium and alumina sub-compartments on the inner glazing pane of the connection, in order to allow for air-circulation in the glazing cavity, as discussed in 3.3.4.3. Using the aforementioned conditions that make a material anchor to test the *b-rep anchor* hypothesis against, "[material] elements [were] mapped onto a [b-rep] pattern in such a way that the perceived relationships among the [b-rep] elements [were] taken as proxies (consciously) for relationships among [material] elements, [and therefore] the [b-rep] pattern acted as a *[b-rep] anchor* [emphasis added]" (Hutchins, 2005, p.1562).

4.3.4. The Case Against Metaphors

According to Malafouris (2013, p.66) "the boundaries of the embodied mind are determined not solely by the physiology of the body, but also by the constraints and affordances of the material reality with which it is constitutively intertwined." Effectively, "it is not the mind that imposes its form on material objects, but rather the latter that give shape to the forms of thought" (Gürsoy, 2016, p.858). In the aforementioned process form and material were weaved together through the use of input spaces, into an emergent blend that contained elements of both. This would not have been possible without the physical existence of the objects that contributed to this process. The fact that aluminium-alumina and glass-alumina FGM have already been invented and fabricated allowed for designing with them in mind, while in the opposite case the design proposed would have delved into the domain of metaphor and speculation. It is also critical to note the importance on a larger level, of using the physical as an anchor for designing within the virtual domain. If that link is severed one faces the danger or reverting back to pre-existent form production in which one's mind is made to operate in the absence of context.

4.3.5. The Background

Additionally, to reinforce this notion of an almost formally unbiased or "objectified" design process it is relevant to note that the four spaces came from physical paradigms the form of which was by no means arbitrary. In the input space of the aluminium-alumina and glass-alumina FGM form was merely absent, at least in the visible scales of the spectrum, as both stem from material science research performed at scales that are imperceptible by the human eye and in which overall shape is irrelevant. In the input space of the enthesis, form and material are completely detached from any influence of the human mind as the connection is generated outside any conscious control, through processes where "the shape of matter is directly linked to the forces acting upon it" (Oxman, 2011a, p.4; Weinstock, 2010) in tandem with the genetic form-giving blueprint of an organism (Carroll, 2007). Lastly, regarding the space of the cladding mullion connection, this is nowadays so standardized an object that it is questionable how much of it is a result of a Cartesian imposition of form over matter. Its shape and characteristics are a result of what is discussed hereinafter as the *Background* (Searle, 1983), which in this case is a vast network of cultural and industrial processes the outcome of which is an almost formless object whose strict function is to weatherproof and to allow access to daylight and external views[64].

What has been shown in this instance is that all ideas related to the design of the cladding mullion detail, stem from processes that are intellectual but at the same time materially driven. Material and form here, become so inextricably conceived, processed, developed and applied that it is impossible to disentangle one from the other.

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64 As mentioned in 1.6.3., the use of the curtain wall originally served the ideological purposes of the international style, which, however, is no longer the case as the style has long been superseded.

4.3.6. Computational Blending

Moving into a particle system software domain, engagement with materiality becomes direct and time-based, while blending this time takes place computationally as opposed to conceptually. Continuing on from the previous workflow, the product of the conceptual blending processes forms the container for a computational blending simulation. In this instance, the resulting form or object is effectively a physical framework, within which material is allowed to self-structure and gradients between materials to be self-formed.

Previously, the description and application of conceptual blending theory in the 'first stage' of the proposed multi-material design workflow, demonstrated how material parameters are always present mentally when constructing the b-rep container digitally. Additionally, there was a point made of a formally unbiased or objectified design process. This stemmed from the fact that in light of the complex series of cognitive processes involved, it is somewhat irrelevant to talk of a main subject that is carrying forward and 'controlling' the task at hand.

4.3.7. The Question of Agency

The aim in what follows will be to elaborate further on this argument and by beginning to investigate *who* is the bearer of agency it will gradually become apparent that one should instead be looking into *where* does the agency actually lie (Malafouris, 2008). This inquiry will be made by looking into the computational blending simulation stage of the proposed workflow and will specifically be concerned with the relation between container and material behaviour, or human and material agency. This will be discussed in the context of two artists the work of which operates on the boundary between control and agency. The point in effect will be to argue that "while agency and intentionality may not be properties of things, they are not properties of humans either: they are the properties of material engagement, that is, of the grey zone where brain, body and culture conflate" (Malafouris, 2008, p.22). Additionally, a further aim will be to demonstrate how this "chrono-architecture" (Malafouris, 2013, p.213) of design operations with form, forces, and materials resembles an ecology of feedback loops of information in which mind and matter operate together synergistically.

4.3.7.1. Conceptual Completion

As discussed in the preceding section, the container for pouring computational materials within and blending them together was designed using conventional CAD elements that initially appeared to be immaterial. By a process of conceptual *completion*, however, this operation was seen in relation to the material simulation that will follow, as well as to the material references that preceded the design. Together with feeds from different conceptual input spaces this meant that the process of designing the container was based on a b-rep forming an anchor onto which material information was projected. This eschewed the idea of form being generated by an individual subject (or from the mastermind's mind (Gürsoy, 2016)), and conventionally worked with and developed in a CAD environment where materiality is only a consideration at the very last stages of this operation when it is too late for it to contribute to anything formally.

4.3.7.2. The Case for the Non-Linearity of the Workflow

Effectively, in the earlier b-rep design process, traces of individualistic formal gestures became minimized to the point of being unrecognisable, with the main argument being of a form generating process that was materially- informed, conceptually- blended, and procedurally- 'transparent' to the extent that any subjectivity behind it was diminished. At the same time, partially relating the generation of form to human intentionality cannot be avoided, however as it will be argued this intentionality is tied up to a larger process of engagement with materials. Who bears agency will effectively end up being blurred in the in-between space of this procedural engagement. Even more importantly, and moving on into the next stage of material simulation, a further point to be made is that the workflow is by no means a linear condition of a vessel preceding simulation and the latter being solely a procedure of computing gradient extents in-between sub-materials of a larger multi-material. Instead the process is one where "every component (biological or non-biological) engages in continuous mutual perturbation, with each component continuously influencing the other's action potential. There are no subjects, no objects, only becoming" (Gosden and Malafouris, 2015, p.704).

4.3.7.3. The Question of Agency- Theoretical Objective

Within this becoming, and although it might appear that the container design and material simulation are made as compartmentalised procedures, it will be shown that the vessel is something malleable that is constantly shaped by the behaviour of material within it. To illustrate this point further, an example of a work by the artist Alberto Burri will be analysed in light of the concept of *material agency* (Malafouris, 2008). The main question to ask initially will be related to the concept of agency and to who is the author or designer of the cladding mullion detail i.e. to what extent is it a product of the designer's intention or an emergent output of the negotiation between human and material agency. The method followed to do this will be to bring to the foreground the container (which as it will be argued is another type of material affecting force) and discuss this against the ideas of *prior intention* and *intention in action*, as well as the idea of the *Background* (Searle, 1983).

4.3.7.4. The Case of Alberto Burri

Burri, coming from the Arte Povera movement was attracted to the concept of "poly-materialism" and produced works that questioned the notion of authorship. The canvas as a substrate for an artistic impression or idea to be painted or imprinted on was reverted into a direct medi-

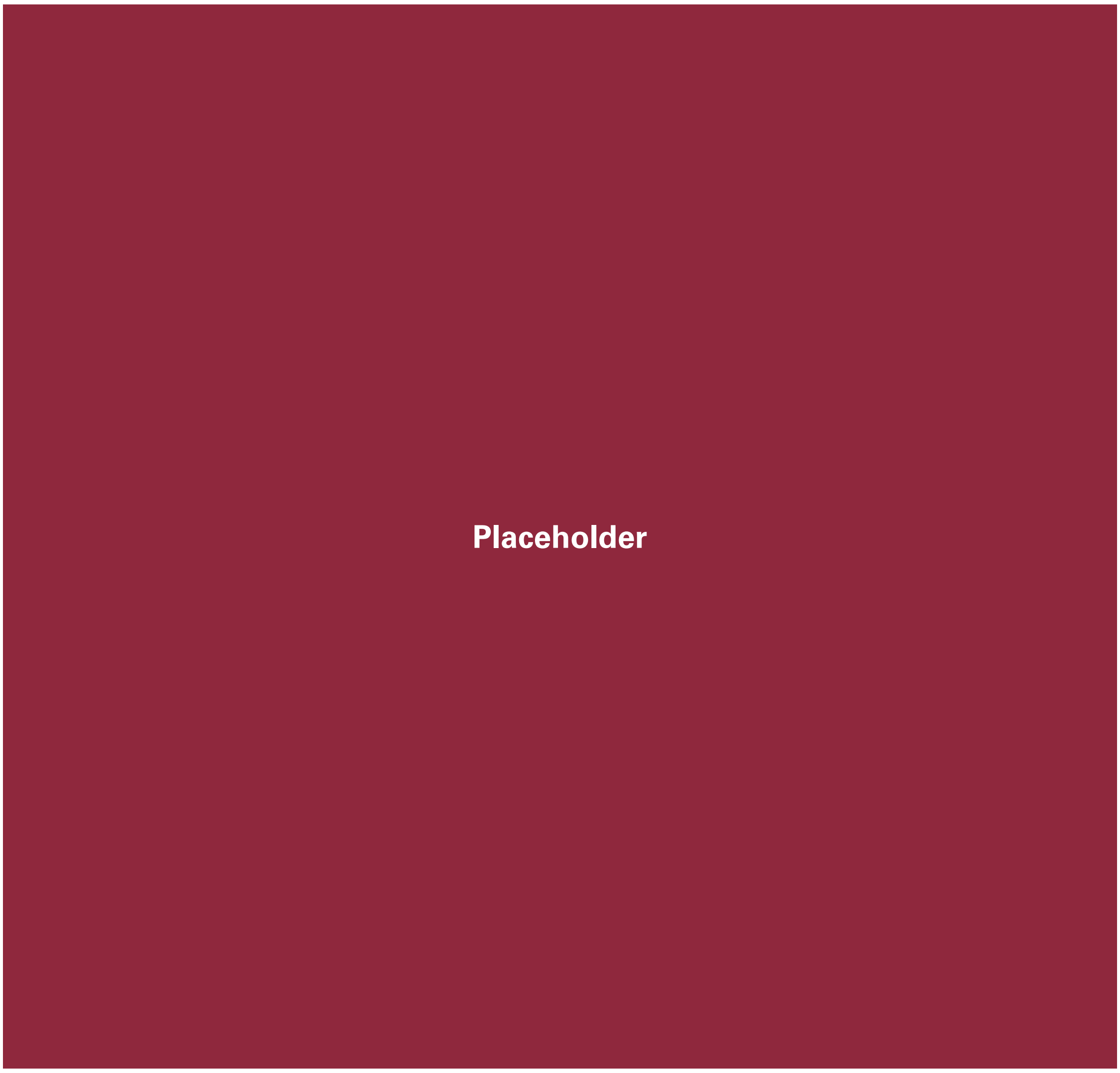

Figure 64: Alberto Burri's *Grande Bianco Plastica* (1962), features a series of burn marks on plastic sheets that have been layered on top of one another.

um of manipulation acquiring creative value per se. What is more relevant in this case was the use by the artist "of natural elements such as fire [that] subjected the artwork to the effects of physical forces, thereby subordinating traditional means of artistic intervention and diminishing the role played by the artist in manipulating materials on a surface" (White, 2016, p.214). More interestingly, in his work *Combustione plastica* (Plastic Combustion, 1958), Burri used a blow-torch to leave a series of burn marks on a piece of plastic (Figure 64), which effectively signified:

> "an abdication of artistic control over the final product. Plastic eradicates the sign of those who burn it; it melts away disappointingly, in an uncontrollable yielding that becomes a meaningless hole, uniform with other such apertures. The material itself determines its shape, according to a principle that is relatively indifferent to human intervention." (White, 2016, p.211)

In this case, there are very similar ingredients at play with the proposed design methodology that namely consist of container, material agency, affecting forces, and human agency or intentionality. Correspondingly, in Burri's artwork the container is the surrounding frame that holds the material in place, the material is plastic, the affecting force is the blowtorch or rather the fire coming out of it and lastly the human agent is the artist 'controlling' the burning process. A slight point of differentiation is that here, human intentionality is 'directing' the affecting force whereas in the proposed design methodology the main intention was concentrated in 'manipulating' the surrounding frame. What can be argued in this instance, however, is that *the surrounding frame or container is another type of force* that contributes directly to what happens to the material. A non-planar, three-dimensional bounding frame in *Combustione plastica* would potentially mean that the blowtorch fire would come into contact with and burn out the plastic in a different manner, thereby producing an altogether different visual and consequently artistic result at the end of the operation. Accordingly, there could also be a scenario in which the combination of the blowtorch flame positioning together with a specific canvas shape would make the flame spread rapidly across the plastic, subsequently reducing the artwork to a formless plastic lump. Or alternatively, if the canvas was held in a horizontal position with the blowtorch below it burning upwards, then the marks would be much more localised and would therefore give the impression of precise control, which is something that would go against *the original intent of the artist*. This would be opposed to an arrangement of the canvas vertically and the placing of the flame perpendicular to it that would allow the burning in the artwork to spread more unpredictably (but at the same time within the limitation of preserving part of the material intact).

4.3.7.5. Prior Intention & Intention in Action

Of primary importance, however, is the aforementioned phrase *the original intent of the artist*, which implies some sort of "intentional state in the mind and an external movement in the world" (Malafouris, 2013, p.137). This intentional state, according to John Searle (1983), can be divided into two types, one being "prior intention" as in an intention formed in the mind that precedes action, and the second one being "intention-in-action", which is something that takes place in everyday scenarios where action is direct and without a prior deliberation. To clarify, the idea of prior intention goes back to the Cartesian dominance over the material world and the mind versus body separation and is something that this thesis is arguing against.

4.3.7.6. Direction of Fit & Direction of Causation

Searle went on to specify the two main properties of intentionality, one being "direction of fit" and the other "direction of causation". The latter is simply the fact that "the intentional state *in the mind*… causes the movement of the agent *in the world*" (Malafouris, 2008, p.29), while the former means "that for a certain intention to be successful, conditions *in the world* must conform to the conditions specified by the intentional state *in the mind*" (Malafouris, 2008, p.29). The point then made is that since action and intentionality take place in the case of Burri (who is dealing with physical materials) in the world, then prior intention can only be intention-in-action as it is realised in this case in burning a piece of plastic. One can perhaps argue that "prior intention" is what generates an "intention-in-action", which Malafouris responds to by suggesting that according to Searle (1983, p.85) "[a]ll intentional actions have intentions in action but not all intentional actions have prior intentions." Additionally, it is quite often the case that an initial intention when applied or exercised in the world may generate unanticipated results, which in their turn might affect or even change the initial intent.

4.3.7.7. Locus of Exchange

To make the case even stronger, there is also the aforementioned idea of the *Background*, which is defined as "a set of non-representational mental capacities that enable all representing to take place" (Searle, 1983, p.143) (it has to be clarified here that for Searle everything taking place mentally is a representation of the world in the mind). In this case, there is a vast array of different cultural, social and political "resources" (Malafouris, 2008) that one can take into account when discussing intentionality. In the example of Burri, they are related to "the horrors of [the second world] war [that] had so degraded Western culture as to invalidate its aesthetic languages" (White, 2016, p.210), the rejection of "the Informel movement's connection between gesture and the artist's psyche…the Italian Socialist party's election campaign in 1953" (White, 2016, p.209) and the list goes on and on. All the above and others are a "number of biological and cultural resources, that he or she must bring to bear on this task, simply to form the intention to perform this task [of burning the plastic]" (Malafouris, 2008, p.31). When this is coupled with the knowledge that plastic was presented as a medium because of its increasing availability due to Italy's rapidly expanding post-war industrial sector, then it becomes clear that it is almost irrelevant to start looking for a starting point of intent, but rather to look for the locus of this exchange between human and material intent. Or "in other words, the line between human intention and material affordance becomes all the more difficult to draw. In fact, we might even suggest that in certain cases, human intentionality identifies with the physical affordance." (Malafouris, 2008, p.33)

4.3.7.8. Material in Tension

Similarly, in this dialectic relation between containing object and contained material, when simulating fusion within the designed vessel, due to the size of the multiple attachment sites between the aluminium and alumina sub-compartments and the viscosity properties of the two materials, in some cases it would be impossible for the sub-materials to flow through the attachments and fuse together. This is something that would cause breakages in the overall connection. The size of the attachment sites would then have to be readjusted, the simulation run again and a continuous form without interruptions would be the result. Effectively, it can be said that in both cases, the material is held in "tension" in-between the affecting force of the flame (the vortex force in the material simulation) and the constraining frame of the canvas (the b-rep vessel being the equivalent of this). Or to give another example, in the case of a potter, the formation of a vessel out of clay is a process in which the centrifugal force of the spinning mould attributes a certain formal tendency to the wet clay, which is then counter-acted with by the hands of the potter. What perhaps differs initially in all three cases is the time frame of the operation, in the example of *Combustione plastica* and in the material simulation the force is directly applied to the material, however, the frame is constructed prior to this application. In pottery, the frame (formed by the potter's hands) is adjusted in real-time, while the material is being influenced by the constant centrifugal force (Figure 65). Furthermore, when discussing this in relation to the "intention-in-action" idea then "it is at the potter's fingers that the form and shape of the vessel is perceived as it gradually emerges in the interactive tension between the centrifugal force and the texture of the wet clay" (Malafouris, 2008, p.34). In the case of the material simulation any sense of tactility is of course removed from the equation as part of the operation takes place inside the computer.

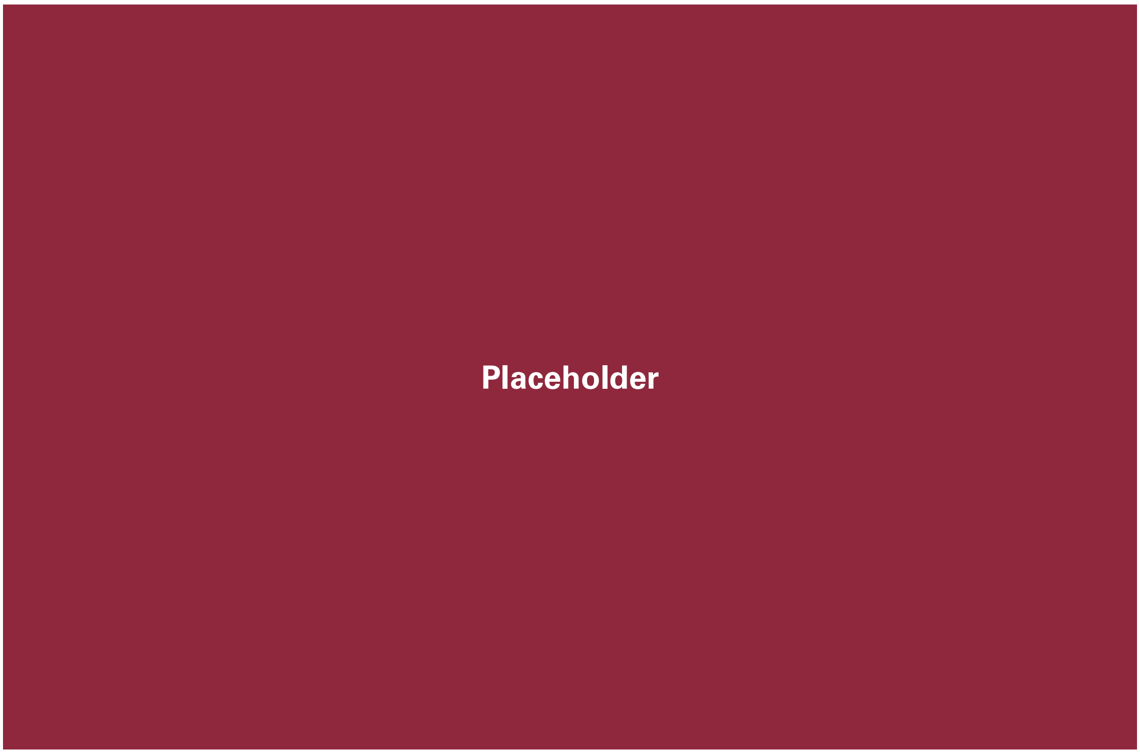

Figure 65: A Clay Vessel in Making, held in tension between centrifugal force and the constraining grip of the potterer.

4.3.7.9. The Extended Mind Hypothesis

But is there such a significant difference between these examples? When discussing the extended mind hypothesis, Malafouris (2013, p.60) suggests that "the body is not, as is conventionally held, a passive external container of the human mind; it is an integral component of the way we think. In other words, the mind does not inhabit the body; rather, the body inhabits the mind." As the hands are parts of the body, so are the eyes, which means that one can simply rephrase the above statement: "it is at the [designer's eyes] that the form and shape of the [containing] vessel is perceived as [the multi-material connection] gradually emerges in the interactive tension between the [vortex] force and the [fusion of the liquid alumina and glass]" (Malafouris, 2008, p.34). The potter putting too much pressure, or Burri building the frame in certain way, would deform the pot and burn out the plastic. When designing through the *b-rep-anchored notional material blending process*, building the b-rep sub-compartments too small and running the blending simulation, alumina would inter-disperse into glass under the vortex force too much to be continuous in a gradient manner and therefore the result would be similar to an alloy as opposed to a functionally graded material.

4.3.7.10. Adequate Blending Characteristics- Main Thesis Criteria

Regarding the particularities of this visual evaluation of the fused material 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 left to right. 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 left, the microstructure consists of isolated *b* particles distributed uniformly throughout a matrix of *a*, whereas at the far right 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 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." (Figures 66 & 67)

This effectively forms a specific piece of criteria against which to assess the result of the material simulation and eventually determine its termination, or not. Additionally, if the size of one of the sub-compartments went beyond a certain threshold (i.e. being too wide) the material contained within would 'dominate' the adjacent ones and effectively become a matrix into which the other substances would be diluted, again in an alloy-like manner (Figure 68). A last condition is that in the case where a temperature fall-off parameter was incorporated (i.e. the temperature of the digitally molten materials reducing gradually so that they solidify as would be the case physically), the substances could coagulate too quickly during the simulation and therefore reach a solid state before fusing together (Figure 69). A response to this would be to of course prolong the temperature fall-off period allowing enough time for merging to take place. Aside from this, the position of the sub-compartments in the interior of the containing vessel would also be 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 (Figure 70). In all these cases, the main criterion for evaluating the resulting material arrangement would be the creation of adequate gradients as specified above. Achieving the right balance to attain this would necessitate a synergy between all the parameters mentioned previously.

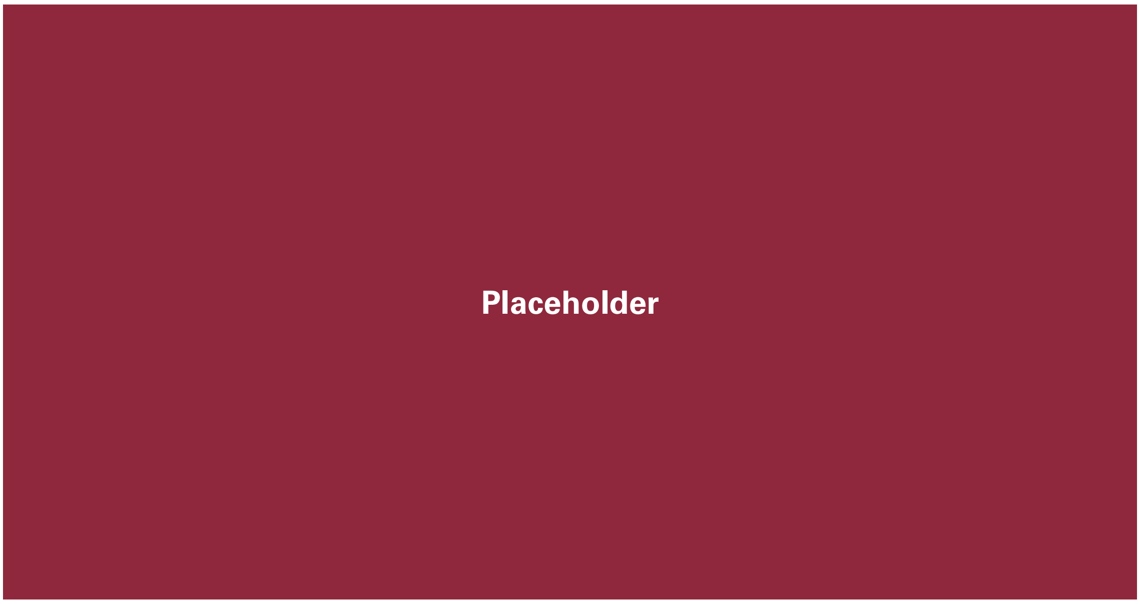

Figure 66: "Diagram of a Hypothetical Graded Structure, that has gradients in several different microstructural features" (Myiamoto et al., 1999, p.42).

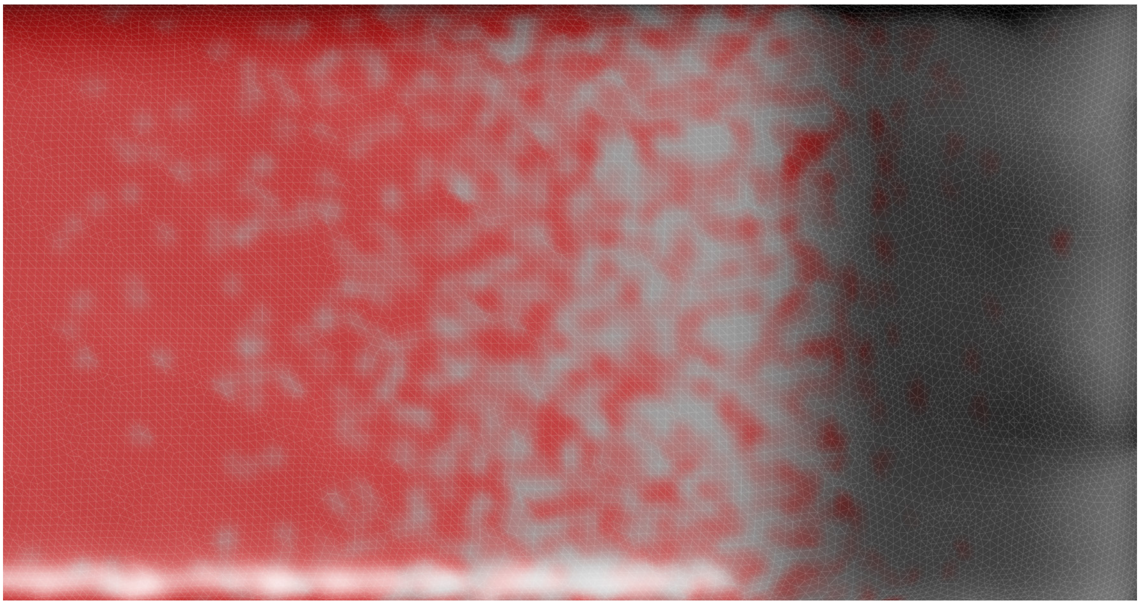

Figure 67: The Graded Structure Achieved in the Blending Simulations that has the same characteristics as the diagram by Myiamoto et al. (1999).

4.3.7.11. Theoretical Reversal of Workflow 'Stages'

Returning to the point of agency situated in this dialectic relation between human and material intentionality and also of the non-linearity of the whole design process, one could in fact start off with the blending simulation and work backwards. A basic, almost form-less container could be used to simulate fusion and by observing the behaviour of materials and their self-arrangement within one could gradually start to give shape and form back to the vessel. This would effectively be closer to Hutchins's (2005) concept of the materially anchored blend, where the observation of the blending of materials would become an anchor for forming a conceptual idea about form mentally, which would then be designed, tested out in the simulation and then

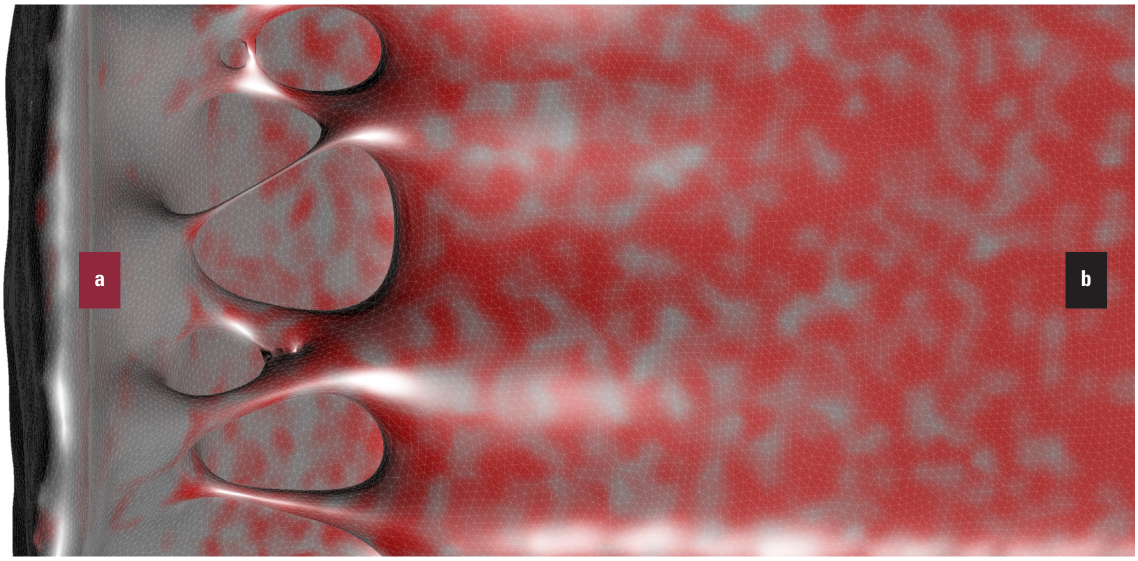

Figure 68: Case 01- Uniform Dispersal of Substance A into B, exhibiting an alloy-like material distribution.

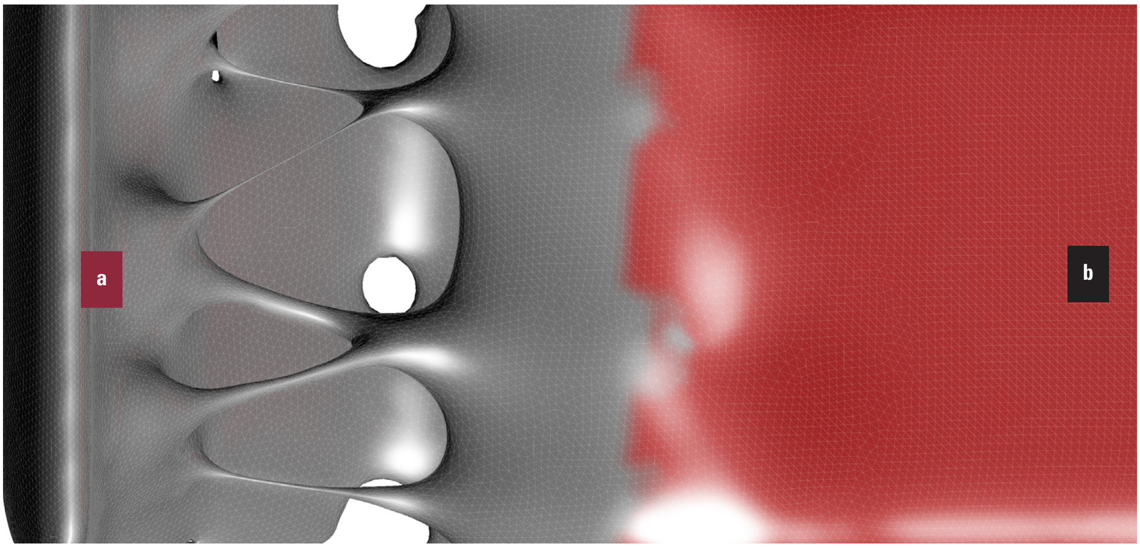

Figure 69: Case 02- Non Dispersal of Substance A into B. The two materials have coagulated before a graded material structure was achieved.

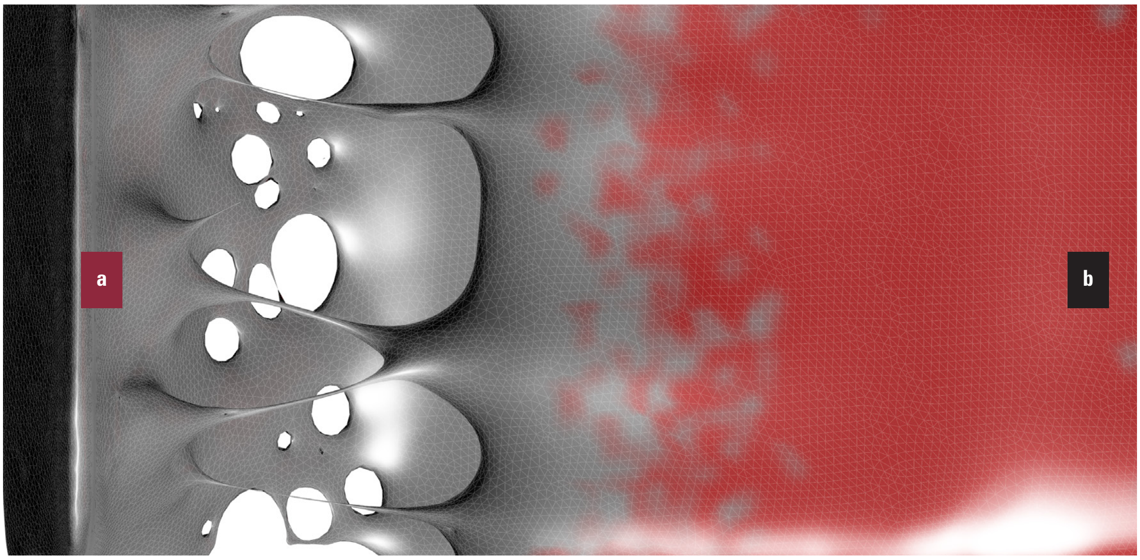

Figure 70: Case 03- Limited Dispersal of Substance A into B. This is due to the thin vessel section resulting in limited material flow of A into B.

re-designed recursively. In a way the dictum of form imposed on matter would be replaced by materiality *preceding, then informing and then co-forming with form* over the time span of the design process.

Another important parameter is consequently the one of time, since a reversed design process would still consist of a number of stages or steps that although conceived in a conceptually integrated manner would be practically and procedurally compartmentalised. A counter reference to this staging would be in the example of form emerging gradually in the hands of the potter, which of course is referring to a 'live' creation of a wet clay object. It is also important to mention how in the case of pottery, any force that the potter is putting on the material is diminishing during the end of the process, when the vessel is almost complete and material is reaching its final positioning solely as a result of the centrifugal force. Here materiality takes over in a mirrored fashion to the start of the process when the potter's influence might have been more prevalent.

4.3.7.12. Potential Practical Reversal of Workflow 'Stages'

In terms of how a similar kind of immediacy can be achieved computationally, there is a new generation of software[65] where the aforementioned lack of tactility is overcome by a physical interface that allows the user to sculpt material in its digitised form (Figure 71). Utilizing a technology that is based on a proprietary version of voxels, the software allows one to exert force on a material by controlling the pressure on a tablet pen. Although technically not yet feasible, one could then imagine that the tactility of pottery making could be transferred over to this marrying up of the physical and virtual. In this scenario, one could be sculpting/forming the vessel virtually in real-time through a physical apparatus and while a digital material blending simulation takes place, making the correspondence between pottery making and the proposed design methodology even more intertwined. Voxels as a computational material technique have been criticized previously due to their incapacity to simulate material behaviour, however in this case they would be employed in sculpting a container the materiality of which is to a large extent trivial. There could of course be another branch added to the series of investigations in the thesis in which the significance of the material composition of the vessel and how this affects the materials simulated within was examined, but at the moment this is not yet technically and computationally feasible. Going back to the real-time vessel sculpting, "intention-in-action" in this case would take place while being immersed in a material behaviour feedback loop, while "in any given stage of this dynamic operational sequence, the [vortex force] may subsume the plans of the [designer] and define the contours of activity or at another point serve as a passive instrument for his or her [design] purposes" (Malafouris, 2008, p.34). At the latter end of the process, in much the same way as pottery and with the vessel having found its final form, one-could release their grasp on the tablet pen and observe fused materiality (under the influence of the assigned computational forces) take over and self-position itself in virtual space.

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65 Such as ZBrush by Pixologic.

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Figure 71: Screenshot of the ZBrush Interface. This new generation of software features a tactile engagement with virtual models, enabling a closer correspondence of digital to physical design.

4.3.7.13. An Extreme Material Engagement- The Case of Kazuo Shiraga

Furthermore, taking this immediate engagement with materials to an extreme, two very relevant examples can be seen in the work of artist Kazuo Shiraga, who was part of the Gutai art group in postwar Japan, as well as in film work by the director Nicolas Winding Refn. Being one of the first to introduce the technique of live painting (Figure 72), Shiraga took a novel approach to this idea with his artwork *Challenging Mud* (1955), which consisted of the artist immersing himself in a pile of mud and cement and using his body to generate an artwork that straddled the domains of painting and performance art. This type of immersive painting that can be said to be the quintessence of "intention-in-action," was in fact part of a larger attempt to "explore individual subjectivity through physical action," (Ritter, 2015, p.23) an idea that is in many ways contradictory to the objectified design process discussed earlier. One can argue, however, that although claiming to metaphorically make a point about the individual, *Challenging Mud* eradicates traces of artistic individuality when seen in terms of process and subsequent output. The clearly discernible figure of Shiraga at the start of the performance eventually became indistinguishable from the muddy medium in which he was submersed in with only an animating presence being visible within the material in the end, thereby blurring the line between the subject (artist) and the object (artwork). Additionally, any sense of achieving a composed arrangement of the mud was impossible due to the immersed relation of the artist's body to the surrounding matrix that did not allow for a detached, overall view of the scene. Shiraga went on to describe the process as such:

> "I started to slide across the surface of it, but that didn't work so well, so I dug my knees into it from underneath, and made holes with my fists, and I also cheated by digging my fingers into it. It turned out to be quite different from what I imagined." (Ritter, 2015, p.127)

Figure 72: A 'Live Painting' by Kazuo Shiraga, showing the registered traces of his body's movement on the underlying medium. This type of painting technique shifted the conventional focus from premeditated composition to the spontaneous arrangement of paint on the canvas, ermerging from the 'dance' of the artist with the medium.

Here, the aforementioned constituents of container, material agency, affecting forces, and human agency or intentionality collapsed into one another, the body becoming the containing frame, as well as affecting force and on top of that being synonymous to human agency. The constancy provided by the centrifugal force in pottery was replaced by the varying intensity of the artist's struggle within the mud, itself depending on his strength or weakness at any given time, as well as the mentally induced stimulus of deciding to continue his effort or not. The hand-eye, tactility-vision coordination that was the case in the controlled act of producing a vessel, became in *Challenging Mud* a full body sensual grappling with the material.

4.3.7.14. Real-Time Immersive Design Engagement

In relation to this and returning to the proposed design methodology, a last domain to cross into would be one where designing the containing vessel would involve a full virtual immersion, with the designer employing much more than the click of a mouse to create space. Of course, in the case of Shiraga, one is referring to an artwork that has no practical function, while in pottery and in the vessel design one is dealing with a rather precise operation and defined output. However, being able to engross oneself in such an immediate manner in material, could allow for a much more three-dimensional engagement with the task at hand and effectively a more profound understanding of the form being designed. This is something fundamentally different to the zooming in and out on a flat computer screen occurring at present. Additionally, bearing in mind the thesis topic, thinking about such a virtual material sculpting capability is possible in this case, due to the very seamless essence of multi-materiality and multi-material space where there is no need to think of componentry and discrete pieces but rather of continuously variable, mud-like matter. Regarding the aforementioned parameter of time, in this virtually immersive bodily "chiselling" of the container in virtual space, the designer would exist physically in a real-time space while operating in a digital domain where the effects of his actions could be directly perceived by rewinding and fast-forwarding material fusion in controllable virtual time.

4.3.8. The Recoupling of Form & Material

Lastly, one could argue that the aforementioned lost engagement with materials in design and the decoupling of form and materiality occurring due to modernist industrial practices and technological developments can be found again and recoupled through the use of digital technologies. Nicolas Winding Refn, in the film Valhalla Rising (2009), makes one aware of the vanishing engagement with the raw materials that surrounds us, by portraying an extreme enmeshing of mind and matter in the coastal landscapes of North America. There, a group of fortuitous newcomers after having consumed a psychotropic brew immerse themselves in mud becoming one with earth, with the director directly making a point that way about this lost engagement in a contemporary social and cultural context (Figure 73). One thousand years after the time that

Placeholder

Figure 73: Scene from the film 'Valhalla Rising', showing the immersion of one of the protagonists in mud.

the film was set at and half a century after the wrong-doings of modernism this relation can be re-established, albeit through the increasing capabilities of the digital to simulate the physical and the increasingly sophisticated mediating physical or not interfaces that are gradually allowing this to take place.

05

VISUALISING & FABRICATING FUSION

5.1. Visualising Fusion

5.1.1. 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. 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.

5.1.2. Visualisation Workflow Objective

More importantly, the visualisation software has an inbuilt way of previewing the different sub-colours (colours in this case representing materials) that the multi-material part consists of. However, this is a time-consuming process[66] that is also inherently unstable (Independent RealFlow Forum, 2011) when it is applied to each mesh[67] in every time frame of the overall simulation. Thus, the colour previewing capability has not been utilised and the mesh has been worked with in default preview (colourless) mode. This in its turn means that similarly to the previous chapter, the mesh is a material-less b-rep entity that one has to mentally project various kinds of information on, in order to manage to render it accurately. According to Hutchins (2005, p.1574), "conceptual models achieve stability by virtue of being blended with an external physical medium. Problems that are…too complex to express at all in internal conceptual models, can be expressed and manipulated in material structure." As previously analysed, using a material or in this case b-rep anchor, will enable the "mapping [of] conceptual elements onto a relatively stable material structure." This will allow for "conceptual structures…[that] cannot possibly be given stable representation using mental resources alone… to be represented and manipulated" (Hutchins, 2005, p.1562). Effectively, the aim will be to demonstrate how conceptual blending theory and *mental material projection* are employed in yet another stage of the proposed multi-material design methodology, in this case the visualisation workflow. In addition, the compartmentalisation of form and material that typically subsumes the conventional architectural design process will yet again be substituted by a seeping through and projecting of material information onto form.

5.1.3. Conceptual Blending- Further Specification

When responding to the criticism that everything appears to be a blend in conceptual blending theory, Fauconnier and Turner (2002, p.350) answer that:

> "brains can put together elements in very many ways other than blending… When we see a table next to a chair, we are organising them as spatially adjacent, but we are not blending the table and the chair… When we remember that we left our house, went to the furniture store, and bought the chair and table, we are organizing events as *temporally adjacent*, but we are not blending our leaving the house with our entering the store... We may further organize the events into a coherent single scenario… but again this brings mental spaces together without blending the sequential events."

---

66 Due to the large number of mesh vertices that need to be coloured, which in this instance are 362,400 in total.

67 The program adds a mesh to the blended particles at each frame of the simulation.

They then go on to state that "of all the ways in which the brain can put two things together, conceptual blending is a relatively small subset" (Fauconnier and Turner, 2002, p.351).

5.1.4. Conceptual Blending- Y-of Networks

Prior to this, they explain their concept of Y-of networks, which are expressions that have the "very simple form: Noun-Phrase of" (Fauconnier and Turner, 2002, p.148). According to this concept, even the very basic phrase 'aluminium is the material of particle system 01' involves a simple form of mental blending. In this case, there is an input space consisting of the more general terms *material* and *particle system* that get projected in a blended space as *material'* and *particle system'*, while also maintaining the original relation of *material-particle system* in the form of *material'-particle system'* in the blended space. They then "provide open-ended connectors from [material'] and [particle system'] in the blend... These connectors are expected to make connections at some point" (Fauconnier and Turner, 2002, p.148). In this instance, the connectors are picked up by the specific values *aluminium* and *particle system 01* that are placed inside the second input space (base space) (Figure 74). The point to be made in effect is that although the whole process of rendering the multi-material part involves the aforementioned "temporally adjacent" mental organisation, when analysed individually each one of the 'steps' of this procedure consists of Y-of conceptual blends. These structure the notional corresponding of each particle system to a sub-material, and to a b-rep segment of the mesh.

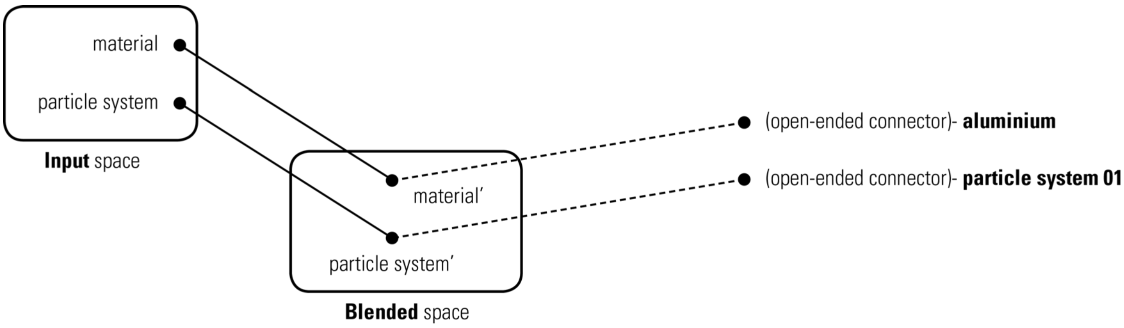

Figure 74: Diagram of a Y-of Network.

5.1.5. Visualisation Workflow

Looking into the workflow per se, the first point that one ought to mention is that the six particle systems are stored in the simulation software sequentially. When importing the particle mesh generated in RealFlow (simulation program) to Maya (where it will be rendered at) 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 (Realflow Melt Shader) is assigned to the overall mesh and fluid sub-material placeholders (six in total in this case) are created within the multi-material shader. Each one of these is corresponding to the six original particle systems that in their turn correlate to six b-rep segments on the mesh. Sub-material assignment, starts 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 continues 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 75). Once this attribution is in place, an inbuilt algorithm generates the gradient distributions in-between the various sub-material segments. As a side note, the standardized nature of this algorithm means that the physically occurring principle of material properties affecting the size and extent of grading within a multi-material is not incorporated into the program, which is something that results in a fixed type of gradient formation. This limitation will be discussed and critiqued in the concluding chapter of the thesis.

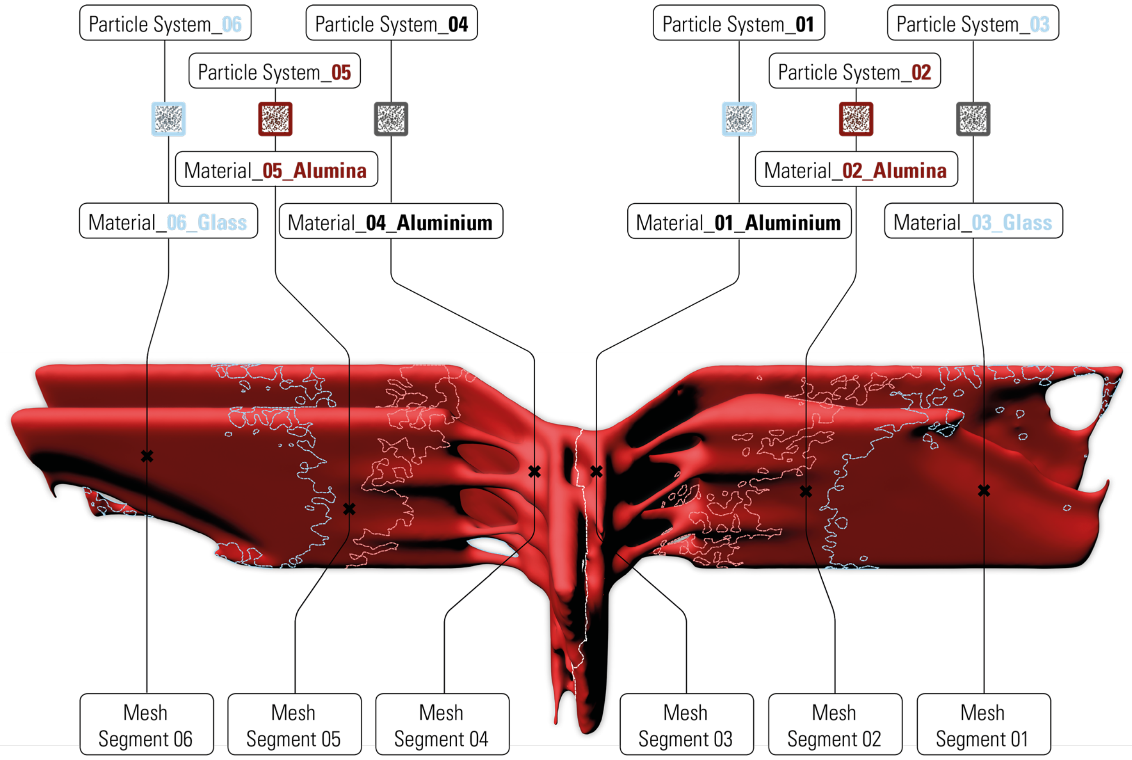

Figure 75: Diagram of the material-less b-rep mesh showing particle system to sub-material to mesh segment correspondence.

5.1.5.1. Y^6 Network Multiple Blend

Going back to the Y-of network principle, all the above correspondences of material to particle system involve basic conceptual blending the structure of which is made up of the previously described input spaces feeding into the blend. Fauconnier and Turner (2002) go on to describe how Y-of can evolve into Y^n networks that consist of a series of links between of-statements, such as "the material of mesh segment 01 of particle system 01." In this instance, it is interesting to note that these Y^n blends are small conceptual packages that are seemingly disconnected to one another. When they are in seen in relation to the overall multi-material rendering, however, they give rise to a blend consisting of six input spaces (each made up of Y-of networks) that feed into the blended space. This is a novel type of conceptual integration network that borrows characteristics both from what the authors term as a mega-blend, as well as a multiple blend. This new network is effectively a Y^6 *network multiple blend*.

5.1.5.2. B-Rep Anchoring

Furthermore, in terms of the sequential mapping of the particle systems on the mesh segments and how the concept of *b-rep anchoring* applies to this mapping, Hutchins (2005) illustrates the phenomenon of using physical resources as a way of reducing cognitive load through the example of the "Japanese hand calendar" (Figure 76). This practice is utilised by students in Japan "to compute the day of the week of any day in the year" (Hutchins, 2005, p.1565) when asked to do so in an exam scenario. The visualisation technique involves the use of some of the regions in the left hand's first three fingers. "The regions are defined by the creases in the fingers that appear at the finger joints. These creases are imagined to make three boxes on each finger. Attending selectively to the first two fingers and the top box on the ring finger creates a field of seven boxes" (Hutchins, 2005, p. 1565). The process that then takes place is the projection of the month names in a specific sequence inside each one of the seven boxes ("the mapping is taught as a sequence of motions of the left thumb over the regions of the fingers. This permits the memory for the trajectory to be redundantly stored in visual and in motor memory"). The weekday names are then mapped within the boxes following another mapping pattern, and through a complex series of mental computations (please refer to Hutchins (2005) for an analytical description of these) in which the hand is used as a material anchor to project mentally stored sequences of months and days, one can work out the day of a specific date in

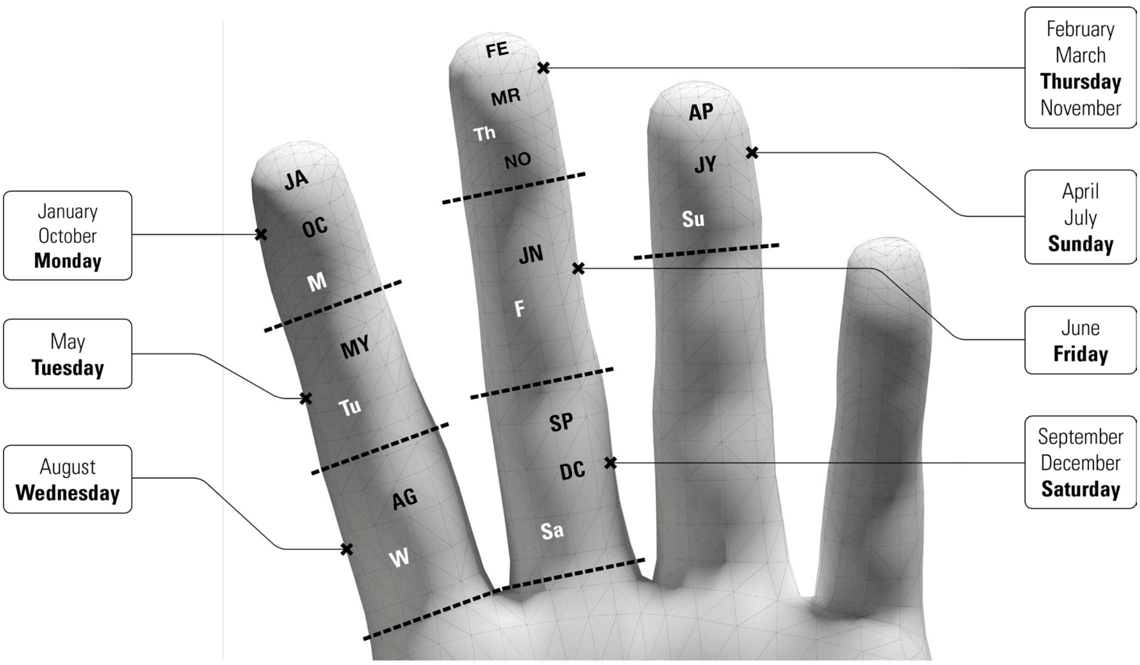

Figure 76: Japanese Hand Calendar. "The mappings of day names and month names onto the fingers of the left hand create a blended space on which the day of the week of any date can easily be computed" (Hutchins, 2005, p.1566)

the calendar year. According to Hutchins (2005, p.1567) "this general phenomenon is so widespread that much of human intelligence relies on 'tricks' of this kind." It is relatively easy in this case to see the similarities between the hand calendar technique and the somewhat more simplistic process of using the *b-rep anchor* as a stable structure on which to project the sub-material segments in the right order.

5.1.5.3. Visualisation Workflow Continued

Going back to the visualisation process, as already mentioned, the glass material corresponding to particle systems 03 and 06 cannot be transparent as the rendering software does not have this capability. One therefore has to render these as solid sub-materials acting as placeholders that will be substituted later on. A subsequent problem, however, is that because of the sub-materials being sequentially assigned and numbered one cannot 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 is to generate an initial render of particle system 01, and particle system 02 (+alpha channel), leaving all other sub-material holders empty. The resulting render is 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 is saved (render 01) (Figure 77) and the next step is to generate a second render of particle systems 01, 02, 03, 04, and 05 (+alpha channel). This means that rendered in the final scene are 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.

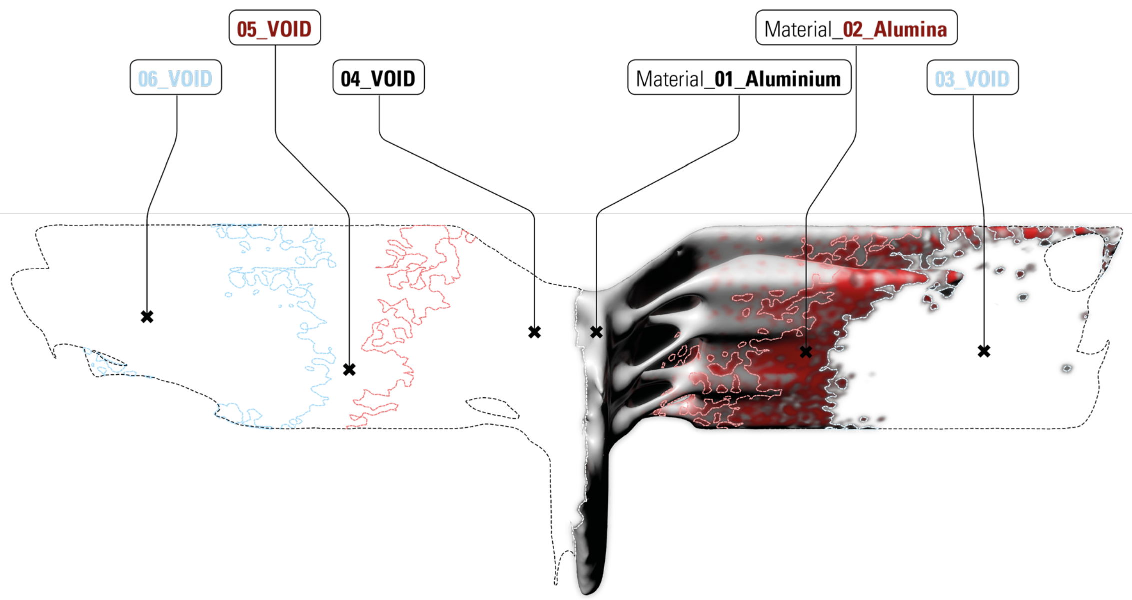

Figure 77: Render 01.

This file is saved as well (render 02) (Figure 78) and finally the multi-material shader originally assigned to the whole mesh is replaced by a full glass material, with the mesh rendered this time as a wholly glazed part (render 03) (Figure 79).

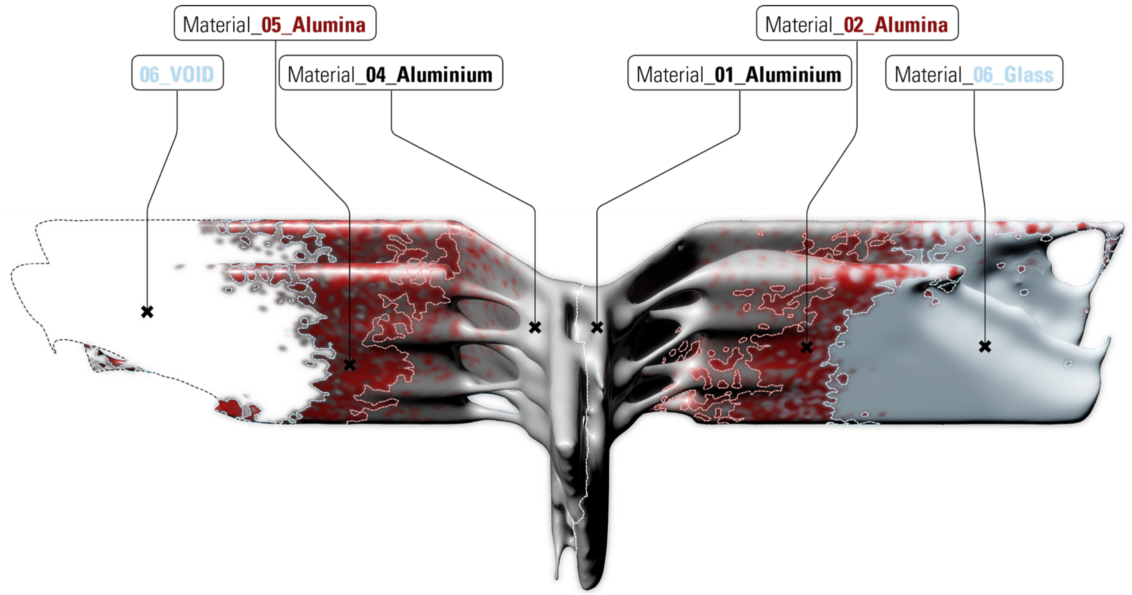

Figure 78: Render 02.

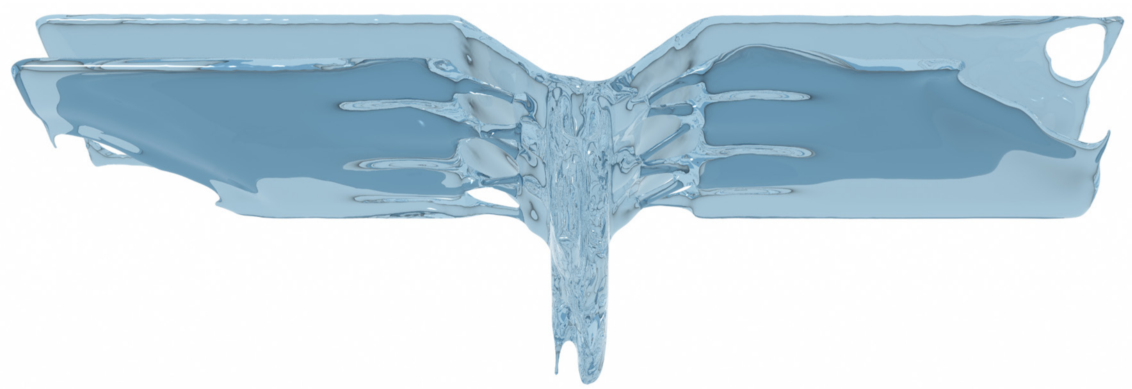

Figure 79: Render 03.

All render files are imported in Adobe Photoshop, the alpha channel of render 01 is imported into render 02, and the channel is 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 are all removed from the image file. Correspondingly, the alpha channel of render 02 is selected, inverted and removed from the file. What one is left with are 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*) (Figure 80).

Render 03 (fully glazed part) is then simply imported into the file, placed under render 02 and glass takes the place of the two voids (Figure 81).

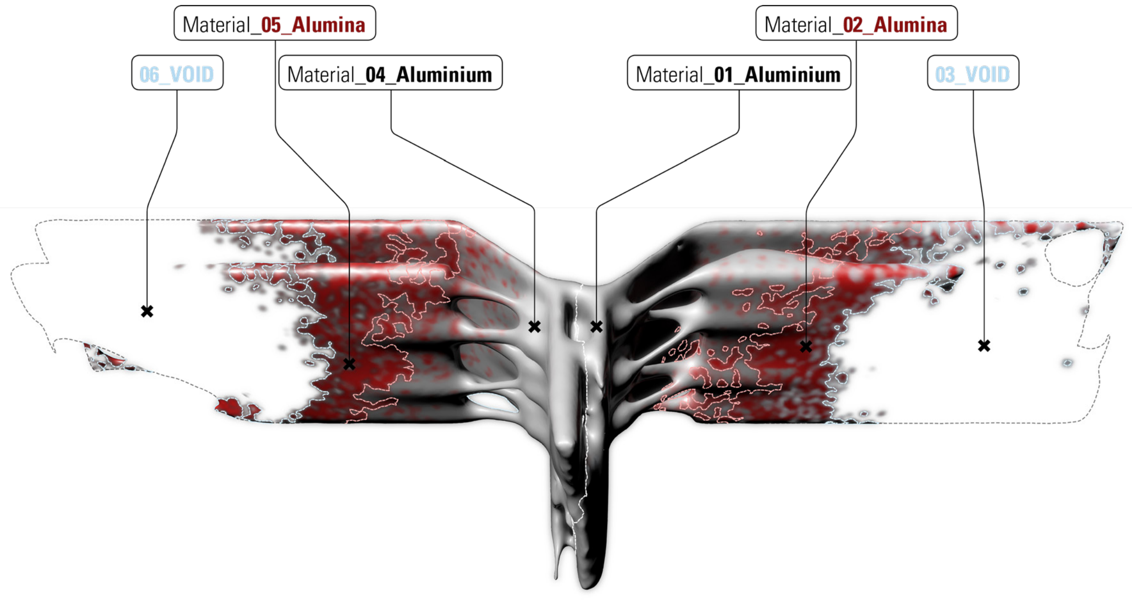

Figure 80: The Resulting Render of the Visualisation Process, showing preserved sub-materials and placeholder voids.

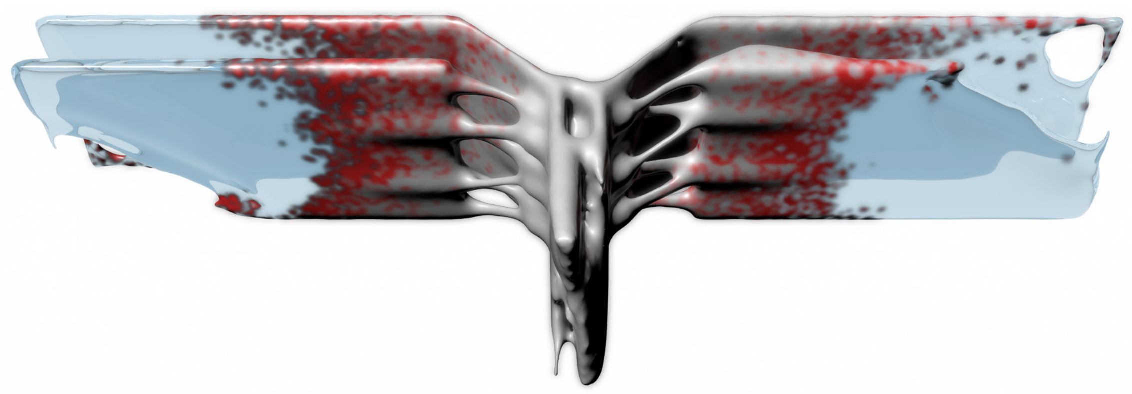

Figure 81: The Final Render.

5.1.5.4. Visualisation Workflow- Conceptual Blending

This last part of the process is yet another blend on a conceptual level, which consists of a basic structure of a generic space (consisting of the general terms 'b-rep' and 'material'), input space 01 (consisting of aluminium, alumina, void, aluminium, alumina, void), input space 02 (consisting of a single glass material) and the emergent blended space of the final multi-material assignment that receives structure and input from both spaces.

5.1.6. Visualisation Process Summary

Summing up this process, the initial material- and colour- less mesh was utilized as a b-rep anchor onto which successive, initially notional (products of sequential Y-of conceptual blends) and afterwards practical sub-material assignments were made. The resulting novel form of conceptual blending, termed a *Y^6 network multiple blend*, then became input space 01 that was connected to input space 02 in its turn consisting of another sub-material sequence. The merging of these two spaces gave rise to a new conceptual blend and effectively the final render (Figure 82). In short, incremental, self-contained Y-of networks were fed into to a multiple blend that was then utilised in the construction of a standard conceptual blend.

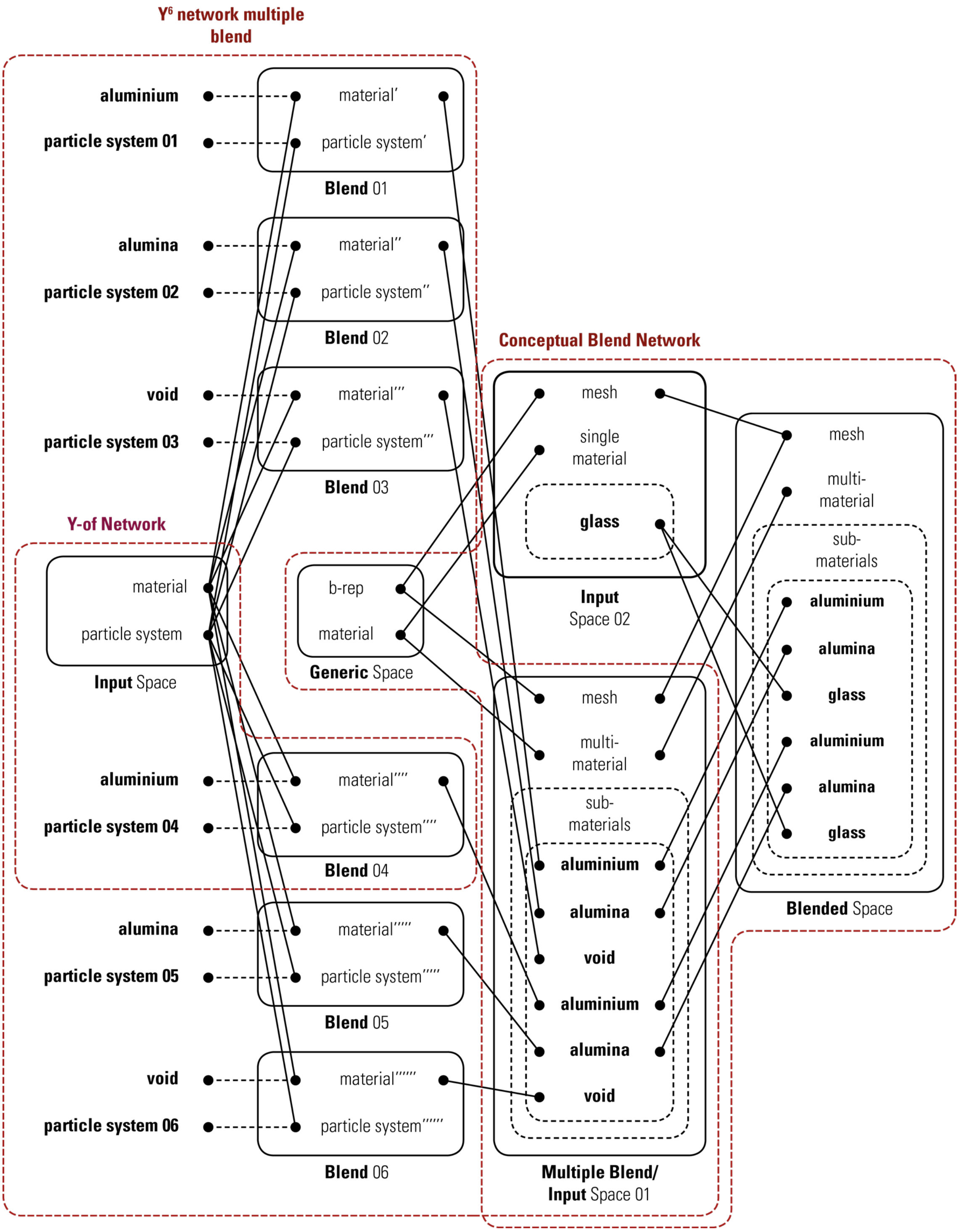

Figure 82: Diagram of the Conceptual Blending Operations, taking place during the multi-material visualisation process..

In terms of the re-engagement of design and materiality discussed in the previous chapter, this description of the visualisation workflow comes to demonstrate further that conceptual blending theory is ubiquitous and applicable to all stages of the proposed computational blending methodology. This is something that strengthens the argument that there is no part of this process in which form exists as a demarcated and self-sustained conceptual or pragmatic entity.

5.1.7. Critique & 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 is not quite an accurate representation of a partly transparent multi-material. More specifically, there are internal reflections that are clearly visible in the rendering of the fully glazed surrogate part (render 03) (Figure 79) that would only occur on a singular material. An accurate representation would of course be one where the glass segments pick up reflections from their neighbouring sub-materials both on a surface, as well as deeper, interior level. On this construal, one could ask what would be a sufficient and acceptable degree of closeness to reality of the final render. 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 3.2.8.). A further point could 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.

5.2. Fabricating Fusion

5.2.1. Autography Versus Allography

When describing the changes brought about in architecture during 20th century modernism, Carpo (2011) states that a main shift has been in architectural authorship that has transitioned from a condition of autography to one of allography. This shift can be traced as far back as the Renaissance and early Humanism (Ingold, 2013), with Alberti being the first to "claim that architects should be not makers but designers" (Carpo, 2011, p.16). After a few centennials, this divide is according to Carpo appearing to come to an end, with digital technologies enabling a reverting back to a premodern, autographic status in architecture. Being closer to artisanal making, and as per point *g.* in 1.3.1., there is no longer the need for translations from two to three dimensions, intervening between the design of a building and its physical manifestation. This is because: "a coherent object on a computer screen is automatically measured and built informationally- and the computer can actually fabricate the same object for good, if necessary, via a suitable 3D printer" (Carpo, 2011, p.33).

This statement, although suggesting a fundamental change in the way building information is 'transmitted', at the same time it still carries with it a modernist leftover. The modular object as the elementary unit that can be aggregated digitally to form a larger virtual construct and consequently fabricated and assembled to form a building, is still intrinsically linked to the aforementioned allographic status of architecture. This is because tectonic assemblage is the applied end result of a design process conceived as and consisting of, component objects that can be easily numbered, catalogued and retrieved in the building site, in many cases without the mediation of an architect. Already back in 1949, Frederick Kiesler criticised this “mechanization of dwelling construction” arguing that:

> “The machine man only designs, he no longer builds but leaves the building to other specialists; he no longer builds for himself but only for others; this is the architect of today […] The resultant home is not an organic whole but a conglomerate. After the floors, walls and ceilings are put in place, man is invited to orient himself in this vacuum and to make himself as comfortable as he can…” (Safran, 1989, p.59)

5.2.2. Fabrication Objective

In response to this and following up from Carpo’s description of a seamless transition between conception, design and materialisation, the following will explore the feasibility of converting the digitally generated multi-material into one that is physical. It also ought to be stated here that as research has shown, alumina can co-exist together with glass in a multi-material, as well as with aluminium in another. However, this research has also shown that graded materials as such have been fabricated in the confines of material science laboratories, using specialised equipment and facilities and in minute scales. In effect, and bearing in mind the inaccessibility of the relevant fabrication means and technology, attempting to manufacture this graded material per se would have quite possibly required the whole thesis to be dedicated to the technicalities of this endeavour and even then, the outcome would be in the best case dubious. Similarly to the approach with the CAD tool, the method followed here has therefore been to utilise widely available, commercial fabrication technology in order to fabricate the simulated multi-material.

5.2.3. Translating Digital to Physical Gradients- Problem Definition

The main problem in this instance was that although colouration that represented graded materiality was visible in the simulation software, exporting it to a 3D printable file format was not possible. This was the case because from all file formats that could be output from the software, none preserved the material/colour values (Figure 83). To generate the necessary bridging between simulation and fabrication, the gradients had to be converted into numerical values that could then be imported into a commercial 3D modelling application in order to output a readable file format for 3D printing.

5.2.4. Translating Digital to Physical Gradients- Computational Workflow

5.2.4.1. Fluid Weight Data

The first attempt towards this conversion was to utilise the per-vertex weight of each particle emitter that can be retrieved as a decimal. The value denotes the degree of influence that the

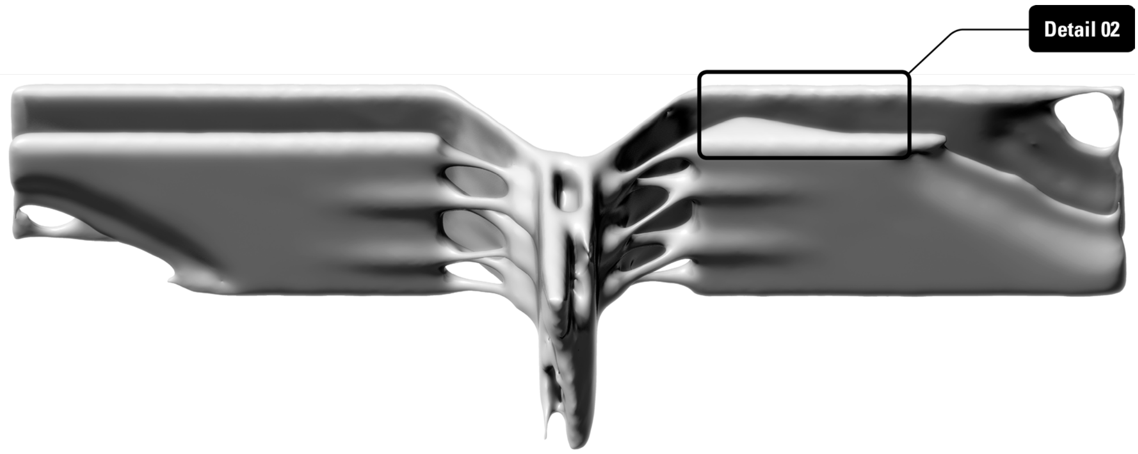

Figure 83: The Mesh Output from the Simulation, does not preserve the colouration representing the materials that have been blended.

individual particle emitters have on the colouration of each of the vertices of the mesh (Figure 84). The Python script utilised to perform this operation was the following:

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

A first run of the script resulted in outputting all weight data 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 the specific vertex colouration would be 100% influenced by particle emitter 06.

At another index of the data list corresponding to a different mesh vertex, the output would be: [('01_Aluminium_Fill_Object', 0.0), ('02_Alumina_Fill_Object', 0.0), ('03_Glass_Fill_

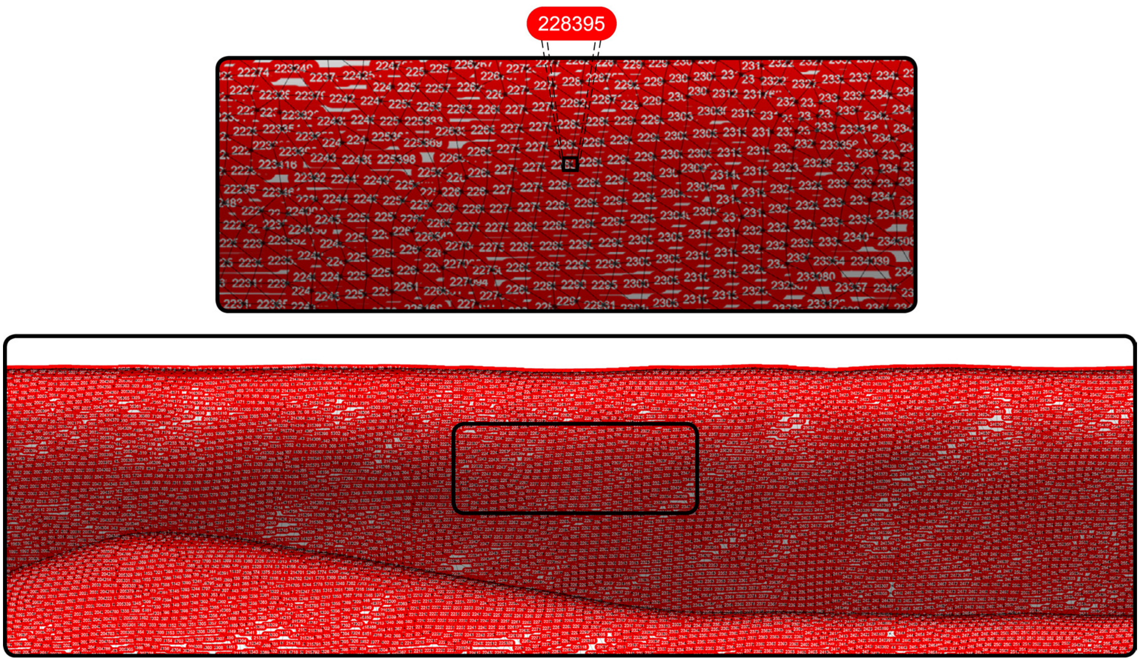

Figure 84: Detail 02 of the Output Mesh, showing the density and numbering of the vertices that the mesh consists of.

Object', 0.0), ('04_Aluminium_Fill_Object', 0.27106717228889465), ('05_Alumina_Fill_Object',0.20003880560398102), ('06_Glass_Fill_Object', 0.52889406681060791)], indicating that the specific vertex is influenced by three particle systems with the addition of the numbers amounting to 1.

When data values were then output and saved in a .doc file, a striking fact would be the very large volume of the file size, which for a total of 297,651 vertices would be 68.1 MB, with the overall word count being 3,411,613 words over 17,576 pages. This would have an impact on file handling times and processing power needed to manage and retrieve the data. Removing the preceding 'x_x_Fill_Object' before each of the numerical values reduced the file size down to 14.2 MB, 1,785,906 words and 6,581 pages.

A sequential correspondence between the fluid data and the mesh vertices meant that in principle, a direct colouration of the imported mesh vertices would be possible. The main problem, however, was that when the data were converted into RGB values although being accurate in terms of the distribution of gradients, the colours themselves were different to the ones of the particle mesh. This was due to the fact that the weight data were an indication of the influence of each sub-colour in the overall pigmentation of the vertex rather than a direct colour value. Colouration would be quite straight forward in the case of a 0.0, 0.0, 0.0, 0.0, 0.0, 1.0 output, as the only influence would be of particle system 06 with an RGB value of (178, 216, 239). The complications would arise when the aforementioned 0.0, 0.0, 0.0, 0.27106717228889465, 0.20003880560398102, 0.52889406681060791 output would correspond to the influence of particle systems 04, 05 and 06, each with a different RGB colour of (87, 87, 87), (133, 13, 83) and (178, 216, 239) respectively (Figure 85).

The initial response to this was to convert each RGB value to an integer and multiply that by the weight data value. RGB (87,87,87) for instance would become 5723991 and then 5723991*0.27106717228889465≈ 154547757. The idea would then be to perform this operation for the other two remaining particle systems and eventually add together the resulting figures in order to acquire the appropriate colour value (Figure 86). This was of course not possible (Figure 87) and in retrospect taking into account that an RGB integer stems from this formula: RGB Integer= Red + (Green*256) + (Blue*256*256) an alternative approach would be to multiply each RGB value by the fluid data value: 87*0.27106717228889465= 23.58284398913383 and convert the results to an integer by applying the results to the formula above: RGB value= 23.58284398913383 + (23.58284398913383*256) + (23.58284398913383*256*256). The problem, however, would still lie in the averaging out of the numbers of the other two particle systems in order to obtain the correct colour.

5.2.4.2. RGB Colours

Eventually, the complexity of this routine was abandoned in favour of a Python script that would output RGB values from the simulation software directly, developed in collaboration with software developer Alex Ribao of Next Limit Technologies. With a much more manageable file size of 10.3MB, the output text file would contain 3 values for R, G and B, which would be convert-

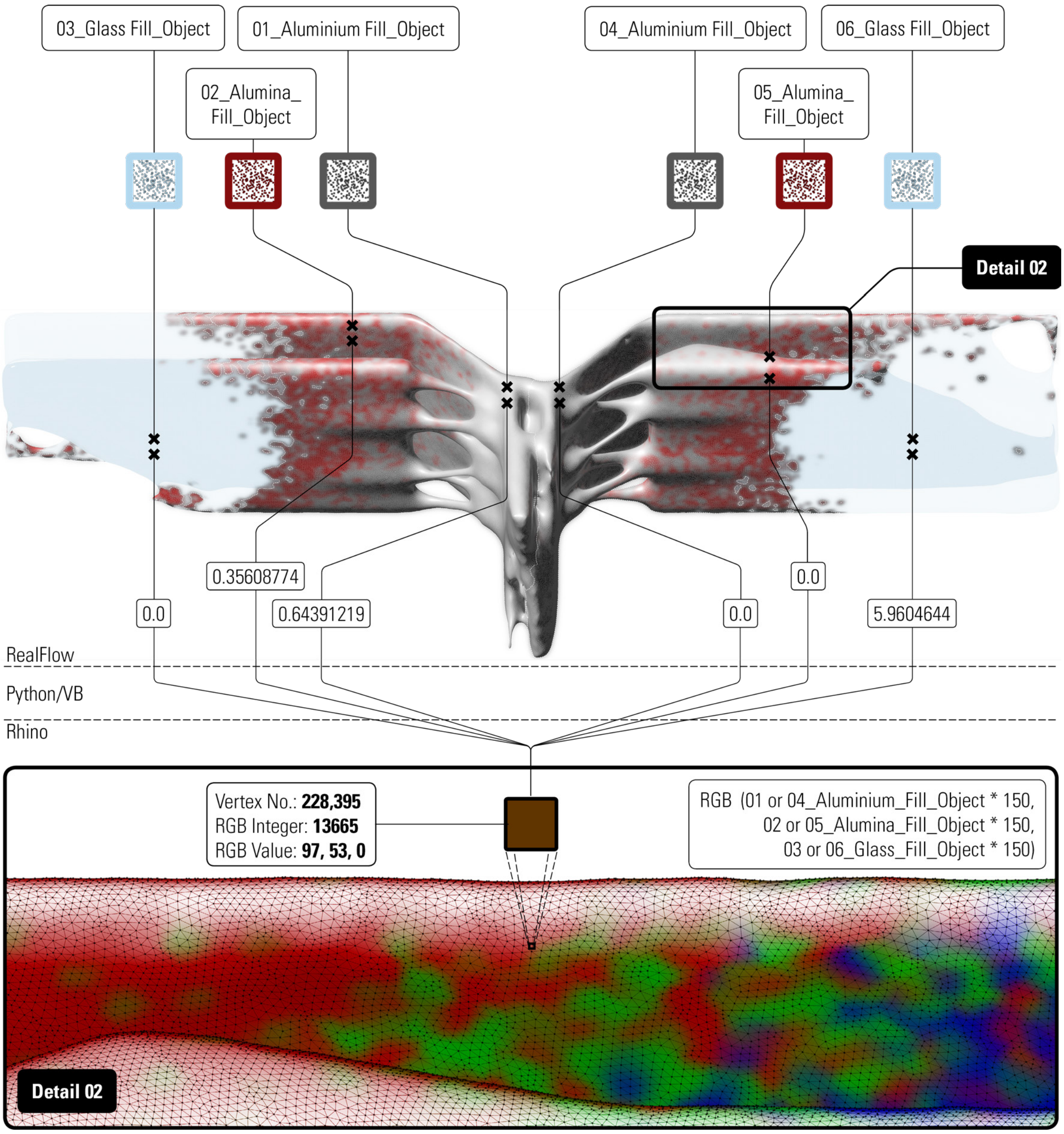

Figure 85: The Fluid Weight Data Workflow, leading to incorrect colouration.

ed from arithmetic into Digital 8-bit per channel values using the following formula: RGB (Vertex R Value (0 to 1) * 255, Vertex G Value (0 to 1) * 255, Vertex B Value (0 to 1) * 255) (Figure 88).

An final problem that appeared during this workflow, however, was that exporting the mesh from the simulation software in .obj format and importing it in Rhino would result in the total number of vertices being up to 15 less than the ones of the original mesh. This non-correspondence effectively lead to incorrect colouration (Figure 89). Consultation with software engineers at Next Limit technologies indicated that there was no direct solution to this problem for .obj formats. The eventual solution was to export the mesh as an .lwo file with the total vertex count being matched in both programs (Figure 90).

This enabled the direct transferring of data from one software into another and was tested out by generating a multi-colour sandstone 3D-print, coloured according to the RGB data list. The distribution and colouring of gradients were visually identical to the ones generated in the

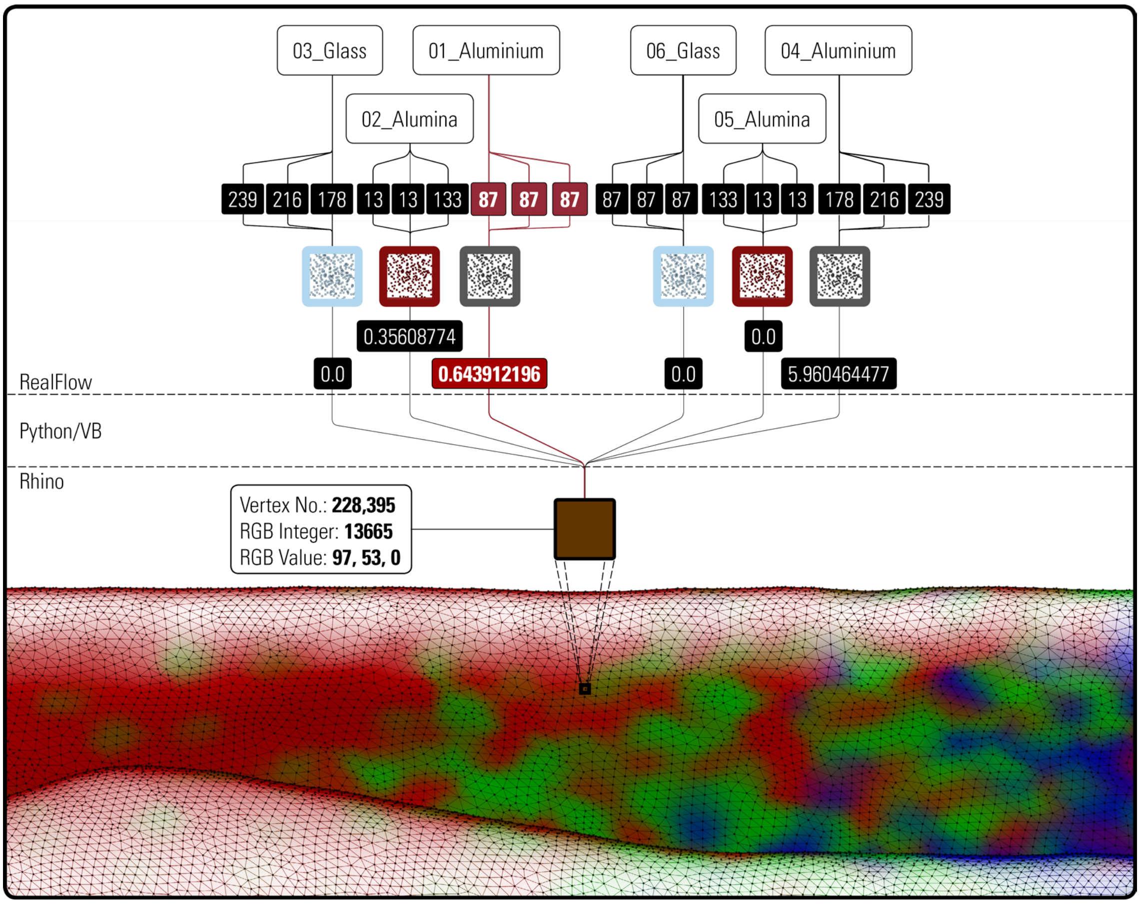

Figure 86: Diagram of the Fluid Weight Data Colour Conversion Routine.

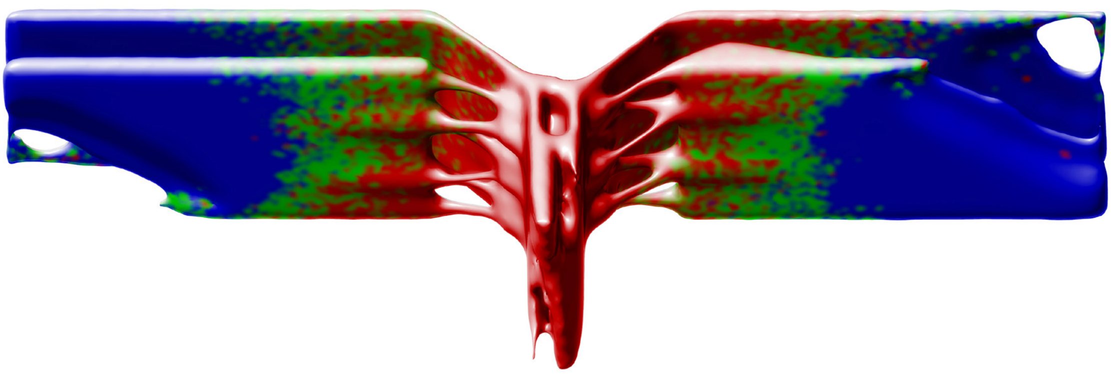

Figure 87: The Incorrectly Coloured Output Mesh.

simulation (Figures 91 & 92), however, the objective as mentioned earlier would be to achieve direct multi-material correspondence as opposed to one that is representational.

5.2.5. Translating Digital to Physical Gradients- Fabrication

When attempting to translate the computer-generated material gradients into ones that are physical, the main problem to take into account is that the 3D printing of gradients is not yet possible. The relevant fabrication methods work with singular materials that are combined to form a larger multi-material entity. The continuously coloured mesh described above would

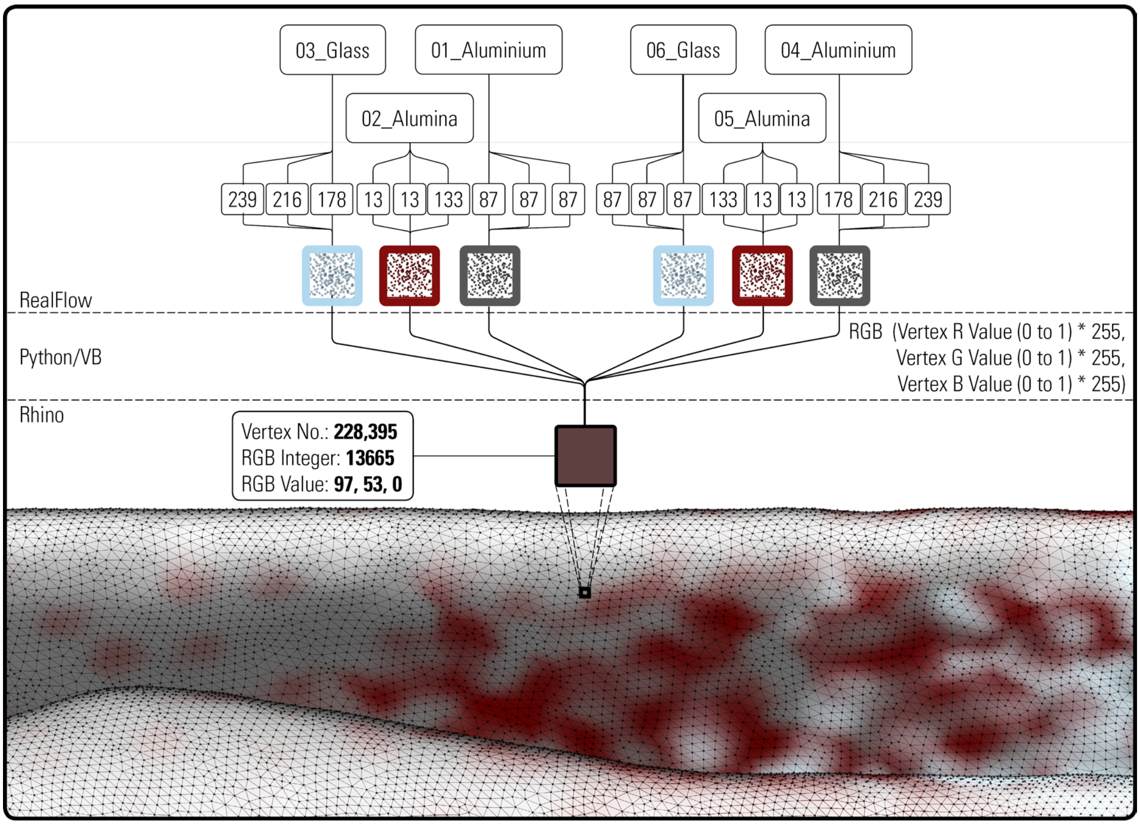

Figure 88: Diagram of the RGB Data Colour Conversion Routine.

therefore have to be discretised by converting the initially continuous, into step-wise material structures. This conversion would affect some of the attributes of the part, while leaving others intact.

5.2.5.1. Stepwise Distribution

Change of properties would naturally be the case when designing with sub-materials that are computationally different to the ones physically fabricated. At the same time shifting to step-wise distribution would have an effect on the structural behaviour within the multi-material itself, as there would be the problem of additional forces developing on the sub-material segment boundaries. Visually speaking on the other hand, there would be no evident difference between the continuous and the stepwise. This is because the material selection from the glazed area towards the alumina and aluminium part could be made optically incremental, therefore still maintaining the effect of transitioning gradually from opacity to transparency. Lastly, regarding the structural characteristics of each sub-material, further research is necessary in order to evaluate the pros and cons of replacing glass with transparent plastic and of aluminium with a Polyjet rigid plastic material.

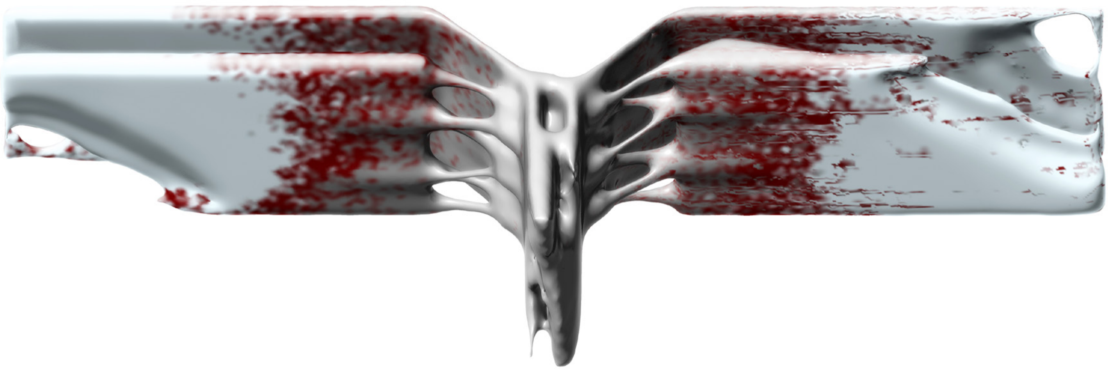

Figure 89: The Output Mesh in OBJ Format.

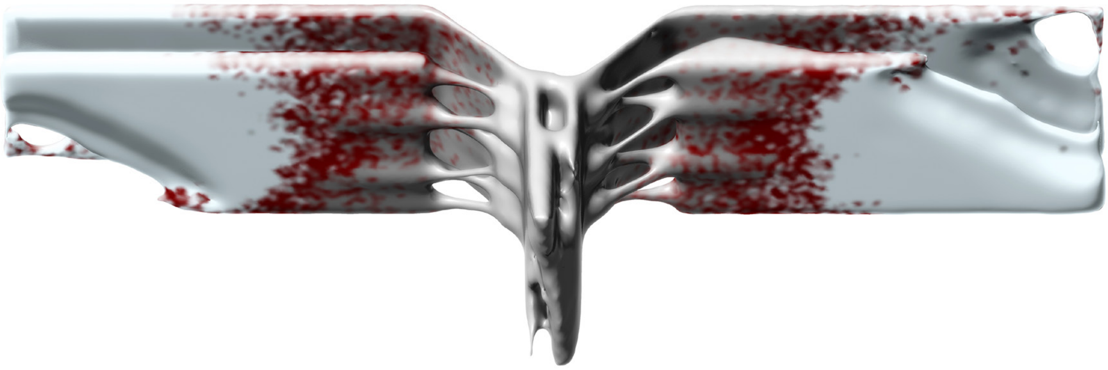

Figure 90: The Final Output Mesh in LWO Format.

Figure 91: The Multi-Colour Sandstone Print.

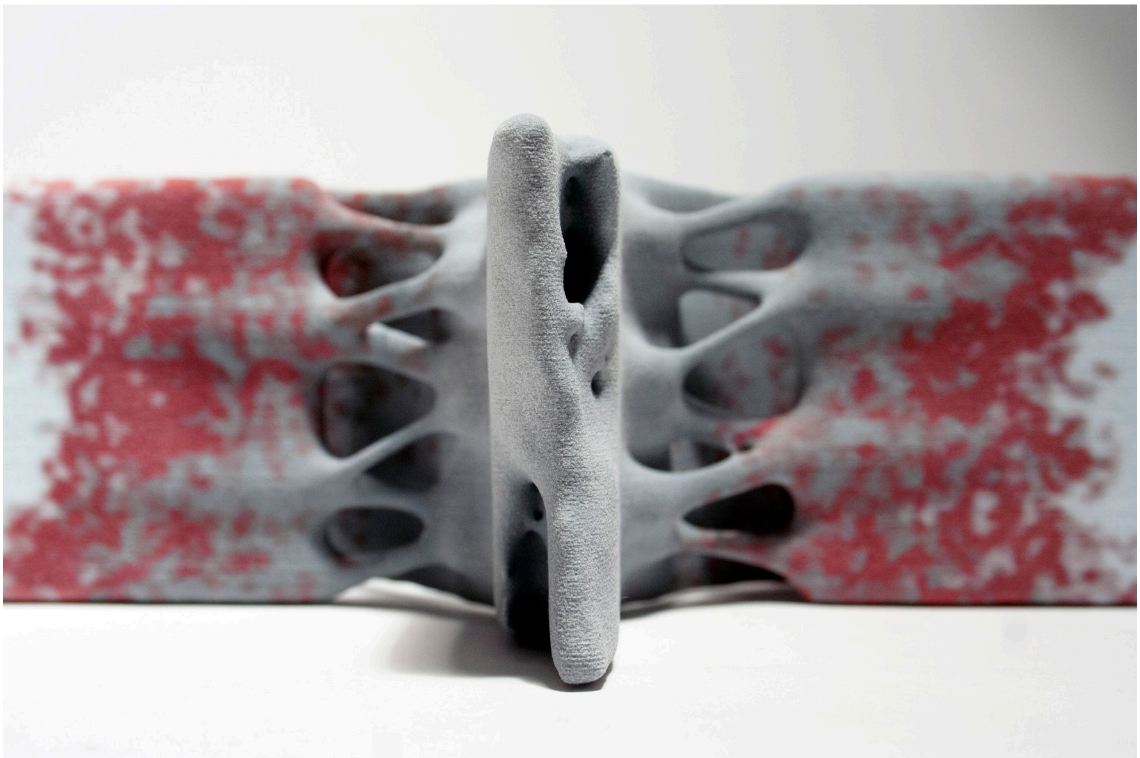

Figure 92: Detail of the Multi-Colour Sandstone Print.

5.2.5.2. Gradient Discretisation Workflow

Consequently, this additional operation of converting the continuous to the step-wise was performed by running a VB script on the graded colour mesh and isolating similar-colour mesh faces. A fact about mesh colouration, however, is that it occurs on face vertices and not on the mesh faces themselves. The RGB colour of each of the three vertices corresponding to a mesh face therefore had to be retrieved, indexed in an array and stored together with the face itself. The stored per-face vertex values would then be tested against an input colour value and if the two would equate, all faces within the same colour range removed from the overall mesh topology and placed on a separate layer. Performing the routine with a different input colour value each time, eventually isolated all similar-colour families into different layers (Figure 93).

5.2.5.3. Gradient Discretisation Limitations

An additional observation at this point would be that the fineness of each of the colour layers would dependent on two parameters. The first was the size of the polygons that the overall mesh would be made of and the second, the degree of deviation of the average mesh face colour to the input colour value. Smaller polygon sizes resulting in a larger number of mesh faces, as well as a smaller deviation of face to input colour value would mean that the overall mesh would be cut down in very fine, almost imperceptibly small segments that would give a better impression of gradation. The flipside to this would be more sub-material boundaries within the larger mesh topology affecting structural behaviour, as well as the available Polyjet materials not being enough to correspond to the large number of sub-materials. Eventually, the script was run

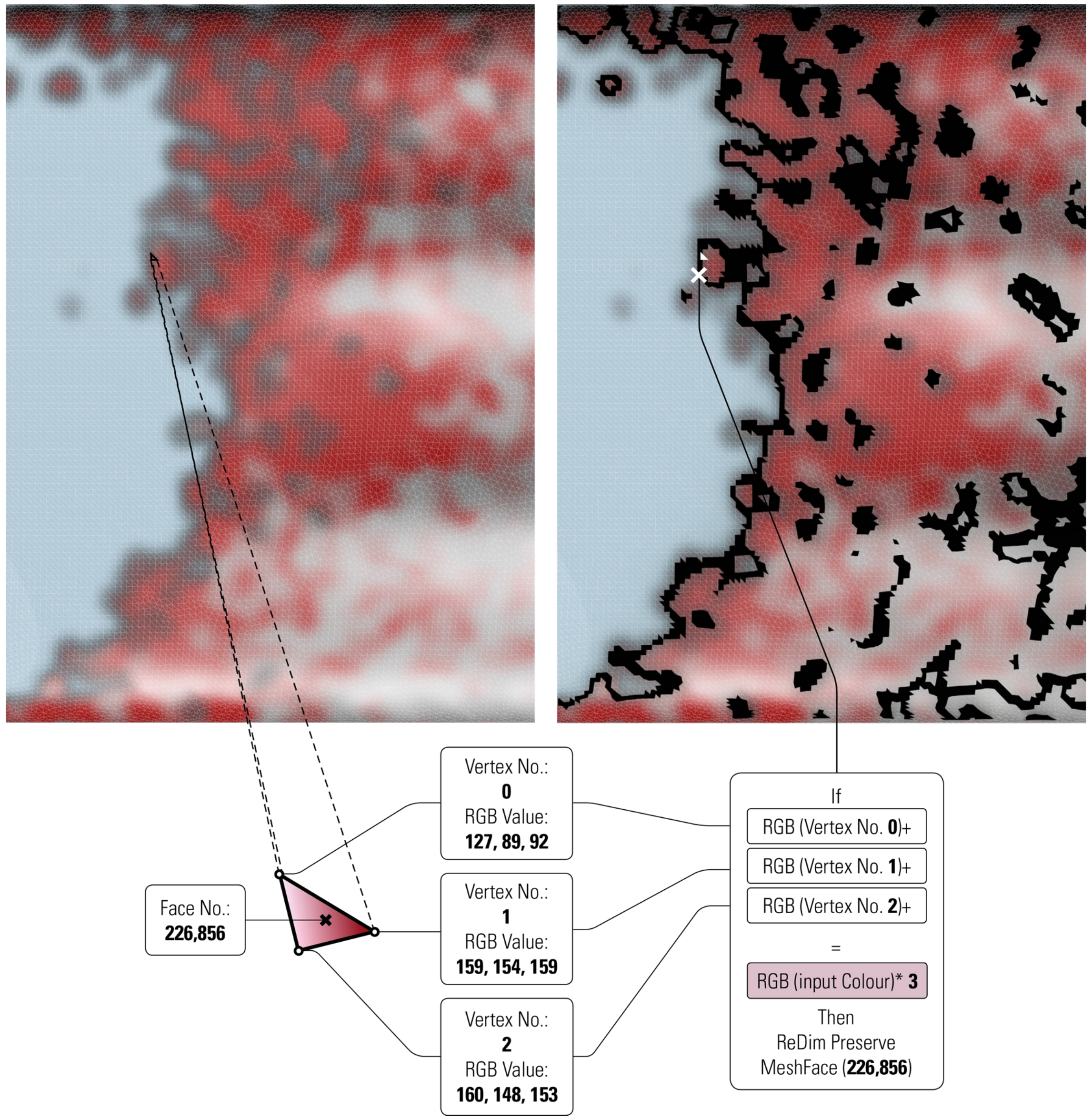

Figure 93: Digital to Physical Gradient Conversion Workflow- Part 01. An average colour value is computed for each of the 99,217 mesh faces, and groups of similar values are then stored in computer memory. The mesh faces belonging to each group are eventually extracted from the overall mesh topology and joined together, resulting in 'ribbons' of mesh segments that are all coloured the same.

for a total number of 9 sub-materials that were corresponding to the original gradients as closely as possible, given the multi-material 3D-printing sub-material availability, mesh subdivision limitations and target colour range (Figures 94, 95 & 97).

Having followed the above workflow, the mesh having been discretised and corresponding materials applied to each segment, a further problem was that the mesh skin pieces had to have a minimum thickness for the multi-material printing purposes. When this minimum of 0.4mm was applied, some of the segments would intersect with their neighbouring ones, which resulted in the materials cancelling each other out (Figures 96, 98 & 99). Further research needs to be conducted in effect into offsetting and clash avoidance routines in order to be able to successfully 3D print the part in its full sub-materiality.

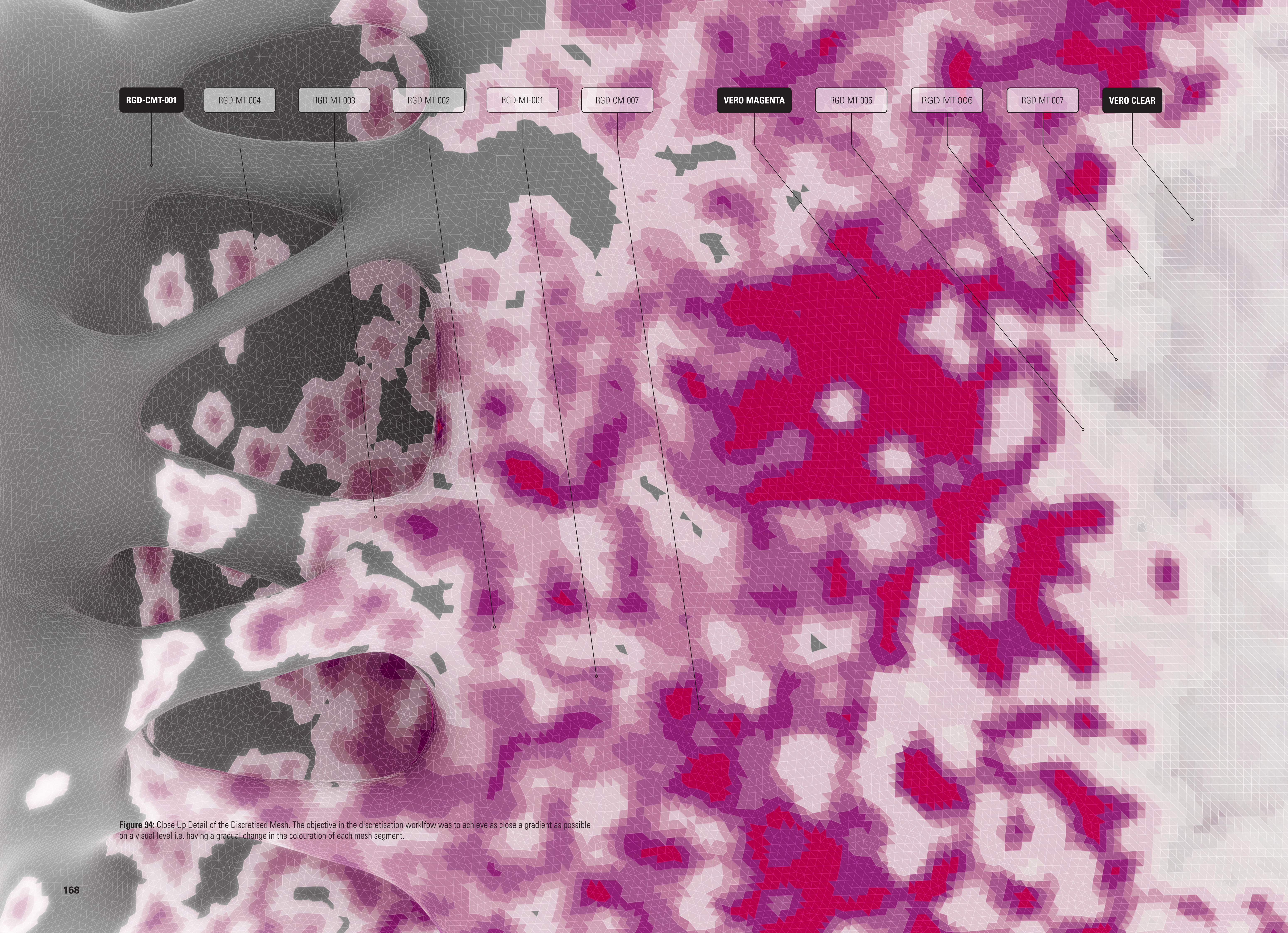

Figure 94: Close Up Detail of the Discretised Mesh. The objective in the discretisation worklfow was to achieve as close a gradient as possible on a visual level i.e. having a gradual change in the colouration of each mesh segment.

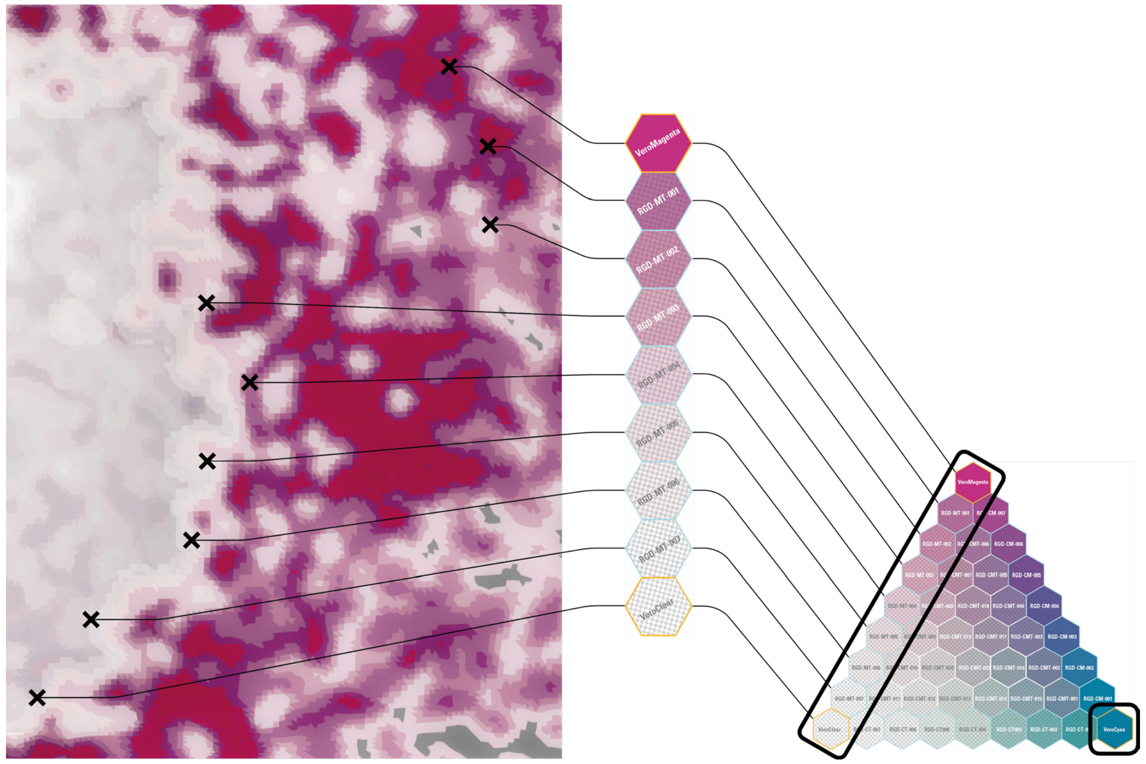

Figure 95: Digital to Physical Gradient Conversion Workflow- Part 02. The palette on the right is from the multi-material catalogue of 3D printing company Objet, and shows the maximum of nine consecutive materials that can be used to achieve a smooth gradient..

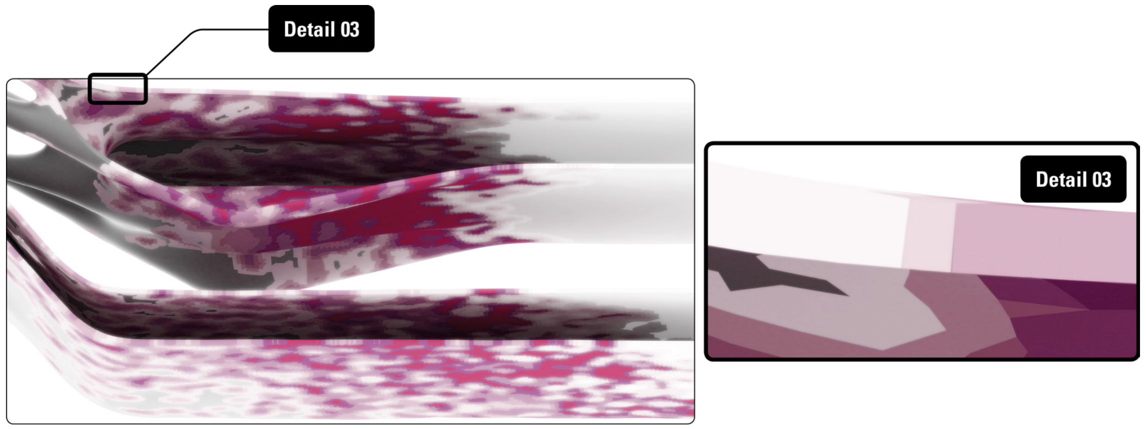

Figure 96: Sectional Details of the Discretised Mesh, showing the intersecting mesh segments.

5.2.6. Fabricating Fusion Summary

Lastly, achieving complete autography is a process that is still in its nascent stages and as it has been presented, a degree of mediation still remains 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.

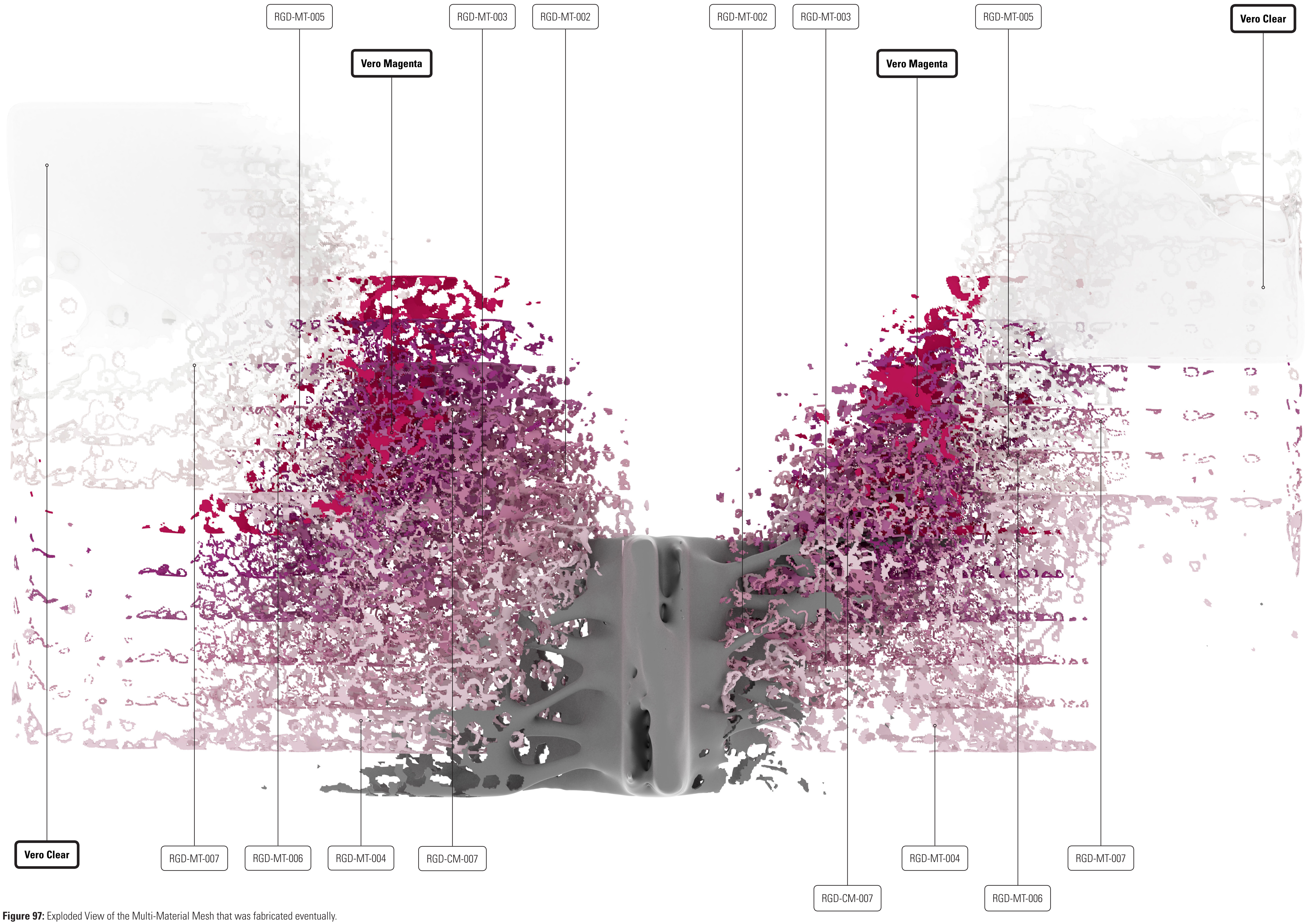

Figure 97: Exploded View of the Multi-Material Mesh that was fabricated eventually.

Figure 98: Close up Interior View of the Fabricated Multi-Material Mullion Interface. The nine initial sub-materials became four, due to offset mesh material overrides.

Figure 99: Exterior View of the Fabricated Multi-Material Mullion Interface. Only one half of the designed interface was 3D printed.

06

CONCLUSION

6.1. Multi-Material Outlook

This is because, at the moment "there is nothing out there that can do true multi-material manufacturing" (Excell, 2013). But at the same time "real innovations will happen in the research world. Multi-material is the next evolution in the technology… you're probably looking at a 5–10 year timescale to see real multi-material integration" (Excell, 2013). As 3D printing technology is rapidly advancing towards this, multi-material design i.e. designing and working with material gradients and translating these from the digital to the physical domain and vice versa, is expected to become increasingly apropos as a research subject.

6.2. Thesis Originality Summary

Anticipating this imminent reality, a *novel* computational design workflow (Figure 100) 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[68] is a 'peer' in the "dance […] between [the] equal partners" (Malafouris, 2008, p.25) of designed form, agency, as well as materially emergent formal and fusional attributes. In effect, as previously stated and following an extensive reviewing of the relevant literature, this is *the first time that a material blending simulation has been used as a design tool, together with conceptual blending theory as a cognitive tool, in a PhD thesis*.

6.3. Main Thesis Contribution

The principle contribution to knowledge in effect, is *the formulation of an alternative design workflow* to the scarce existing methods of designing with multi-materials in the computer. Eschewing the typical voxel-based arbitrary assignment (as outlined in 2.2.4.1. and 2.2.5.1.) of material gradients, the CAD method employed in this workflow harnessed the capability that present day computation offers of emulating physical phenomena. More specifically, the use of particle system elements allowed for the (partly) bottom-up formation of gradients that emerged as a result of material properties and rheological behaviour. As described in 3.2.3., the originality of this approach is that there has been a shift from the practice of deploying lines as the main medium to design with, to the construction of digital blending vessels that were used to mix virtual materials within. This shift towards the practice of "cooking in a bag" was first coined explicitly by Lynn (2010, p.19) when referring to the assimilation of composite materials in construction. Here, due to the current material range limitations in multi-material 3D printing technology a focus on physical materialisation was eschewed, and "cooking in a bag" referred to the proposed method itself of designing with multi-materials.

This design approach abides to the notion that asking materials what they want to do is essential to the imminent multi-material design process, with the differentiation to prior takes on this notion[69] being the mediation of the computer that allowed materials to answer this question through the use of digital simulations. Rather than being a purely bottom up method, however, and partly because the model proposed was targeted towards the redesign of an envelope detail, which meant that a degree of control was required, there was an added 'restraining' component (the mould discussed in 3.2.2. and 3.3.5.) that initially appeared to be a top down design artefact. Using specific instances from materialist theory and the philosophy

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68 I.e. the natural propensity of substances to acquire specific forms that relate to their chemical and atomic structure characteristics.

69 Referring here to Louis Kahn's widely known statement about bricks: "If you think of Brick, you say to Brick, 'What do you want, Brick?' And Brick says to you, 'I like an Arch.' And if you say to Brick, 'Look, arches are expensive, and I can use a concrete lintel over you. What do you think of that, Brick?' Brick says, 'I like an Arch.' And it's important, you see, that you honour the material that you use. [..] You can only do it if you honour the brick and glorify the brick instead of shortchanging it."

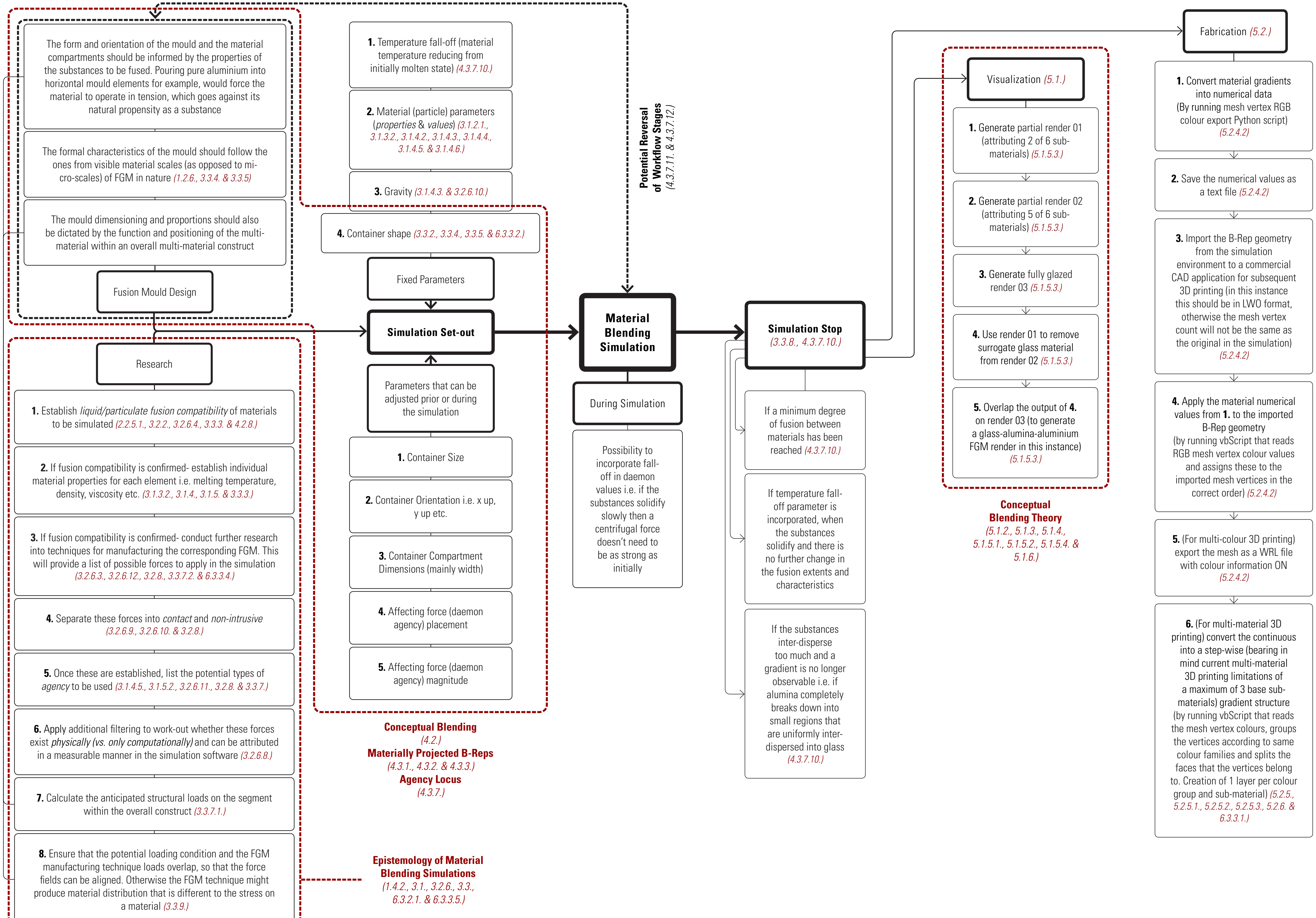

Figure 100: The Complete Multi-Material Design Workflow, and corresponding thesis chapters.

of the mind (namely Malafouris's (2013) Material Engagement Theory and Searle's (1983) prior intention, intention in action and Background concepts) the ensuing argument demonstrated that the B-Rep component emerged through a reciprocal dialogue between material affordance and human intentionality (4.3.7.5., 4.3.7.6., 4.3.7.7., 4.3.7.8., and 4.3.7.10.).

6.3.1. Theoretical Contributions

In terms of any second order contributions to knowledge that derive from this main achievement, on a theoretical level, this has been the use of a specific strand of cognitive theory (namely conceptual blending) and the creation of a series of diagrams (in 4.2.8. and 5.1.6.) that map out one's thought process over specific instances of the proposed process model. The contribution here in effect, is to cognitive theory discourse and more specifically in studying the mental operations taking place in specialised disciplines (in this case architectural design) that involve thought processes that are different to ones taking place on a quotidian level.

Additionally, designing with functionally graded materials and examining this process through Material Engagement Theory and Searle's intentionality propositions, has provided a new take on the question of authorship in the creative disciplines. This in effect relates to the fact that new types of materials and the incorporation of these in architectural design, also instantiate a new discussion about the role of the architect-author and the degree of control that one has over the form generation process. Here, it was demonstrated that even the aforementioned B-Rep container that appeared to be generated through a top-down manner, effectively emerged through the existence of the Background (4.3.5. and 4.3.7.7.) (that enables the designer to form the intention to initiate this design task) and the recursive dialogue between designed form and the emergent types of multi-material fusion.

6.3.2. Design Contribution- Epistemology of Material Simulations

Further second order achievements on a design level, were the formulation of a set of prerequisites (epistemology) that an architect deploying material simulations to design multi-material constructs needs to abide to in order to set out valid conditions for these simulations. More specifically, when blending materials together using computer simulations, the three main inputs that are central to the process are *1.* the parameters controlling the material behaviour, *2.* the formal characteristics of the vessel that the materials will be blended within, *3.* the fusion compatibility of the substances to be mixed, and lastly *4.* the assigned agency (or forcefield) under the influence of which materials will start mixing together.

6.3.2.1. Material Properties Assignment

Regarding the first parameter, it has been argued (in 3.1.4.1. through to 3.1.4.7.) that the endeavour of the multi-material designer ought to be the attribution of virtual fluid properties as accurately as possible. At the same time, it has been acknowledged that a complete precision in this attribution remains a futile attempt, even when looking into disciplines such as physics or material science. In addition, the creative discipline origin of the CAD tool utilised in this research meant that there was a partial degree of accuracy that was complemented by a recursive trial and error process in order to attain a sufficient output (the evaluation and verification of what is a sufficient outcome is discussed in 6.7.). Admittedly also, it can be argued that the more precision in defining a simulation environment a software offers, the less the degree of design flexibility. In effect, what has been proposed is that a valid simulation set out should consist of the accurate assigning of all scientifically measurable fluid properties (3.1.4.3.), and the relational assigning of all other non-measurable but quantifiable properties that are software specific (3.1.4.4.).

6.3.2.2. Mould Form

Regarding the second parameter, the argument has been that there are several effective solutions to bi-material attachments that are found in nature (3.3.4.3.) and that can be referred to when designing the B-Rep moulds. Additionally, practical considerations such as the fact that there had to be a series of openings in the connection for air to circulate through the cavity and prevent any condensation from building up (3.3.4.3.), as well as the structural loads acting on a typical curtain wall (3.3.7.1.), informed further the characteristics of the container. Here, it ought to be mentioned that there is an inconsistency in performing a structural load analysis on the typical discrete and homogeneous materials that make up a curtain wall, but consequently designing with a multi-material that potentially exhibits a different structural behaviour. This has been the case because, as mentioned briefly, performing structural analyses on complex graded material entities is a highly-specialised and notoriously difficult process. In effect, the two requisite conditions in designing a material simulation blending vessel are to draw from natural bi-material attachment paradigms, and to perform load analyses on the segment to be designed through a multi-material. An additional third condition that can influence form is the consideration of functional parameters that can vary from transparency and porosity in an envelope, to acoustic separation and illuminance in a ceiling segment.

6.3.2.3. Fusion Compatibility

In terms of fusion compatibility, the simple requisite has been to verify this through research into existing material science paradigms of functionally graded materials that have already been manufactured (3.2.6.3., 3.2.6.11., 3.3.3., and 4.2.8.). A more sophisticated and automated take on this would be the example of a virtual material library (3.2.2.) that could be plugged into the simulation environment for an instant verification of material compatibilities.

6.3.2.4. Agency Assignment

Regarding the agency assignment, the first step has been to again conduct structural analyses in order to work out what are the forces that are acting on the segment that is being designed through a multi-material and the replication of these forces within the simulation environment.

This way, gradients are being formed under the influence of gravity together with the anticipated loads that will be applied to this part when physically constructed.

Regarding this parameter of constructability, further specificity in the method utilised for manufacturing the segment means that there would be two cases to take into account. The first one would be an imminent future in which the segment would be 3D printed, which would mean that identification of structural loads would suffice for assigning agency. The second case would be a present one, where FGM are manufactured using techniques such as accumulative roll bonding (3.2.6.3.) and centrifugal casting (3.2.6.11.) among others. In this case research into existing functionally graded material manufacturing techniques would be a further requisite in order to correspond the simulation agency to physical reality. Here, the main argument has been that the condition that needs to be met is the differentiation of forces into contact and non-intrusive (3.2.6.9.), and the selection of the latter as the appropriate agency (3.2.6.10.). When this has been determined, an example would be the case where the structural loads acting on a multi-material segment would be different to the ones developed during FGM manufacturing. Loading would distribute gradients one way, and centrifugal casting (for instance) in a different one. The criteria and selection process of the manufacturing technique of the multi-material segment by a designer would in effect be the correspondence of structural loading force value and directionality to the one of the FGM manufacturing method. As described in 3.3.9., an example of this was the correspondence of the centrifugal force employed in the centrifugal casting of FGM to the displacement analysis performed in 3.3.7.1.

6.3.3. Design Contribution- FGM Visualisation Method

Additionally, a further contribution on a design technique level has been the formulation of a visualisation workflow for the (partially) accurate representation of a multi-material construct that incorporates a transparent segment in its volume (as described in 5.1.). This method involved the use of a combination of different types of renderings of the same artefact generated in a 3D modelling software (Autodesk Maya) and the sequential processing of these in a 2D graphics software (Adobe Photoshop). If at all possible previously, a rendering of this kind (of a multi-material that is partly transparent) would require access to specialised software used in the visual effects industry. Through the proposed workflow, this can now be made with standard software widely used by architects and designers.

6.3.4. Design Contribution- Material Simulation to Fabrication Method

On a design technique level again, regarding multi-material fabrication, the contribution has been of a new workflow connecting material simulation to additive manufacturing (5.2.). More specifically, following extensive research and consultation with Next Limit Technologies (the company that produces RealFlow, the simulation software used for all multi-material simulations in the thesis) a computer code written in the programming language Python was devised for converting gradient colour data (representing multi-materials) into numerical data. A further script written in the programming language Visual Basic (RhinoScript) was deployed for repainting the exported numerical colour data on the material-less mesh (see 5.2.4.2.) in a commercially available 3D modelling software (Rhinoceros 3D). This was in order to assign multi-materiality back to the 3D model. Another computer script written in Visual Basic was deployed to divide the mesh into discrete colour segments (with each one corresponding to a sub-material in the available multi-material palette by Objet) and effectively convert it into a 3D printable format. The latter part of this fabrication routine (mesh discretisation) is something that has been researched into by other designers previously, however, the conversion of gradient material information from a simulation program to 3D modelling software is a novel contribution of the PhD.

6.4. The Expository Nature of the Designed Artefacts

During the above workflow, it was deemed necessary to generate a number of physical artefacts that were used to test and evaluate specific stages of the process model proposed. These artefacts that have been presented in 5.2.4.2. (multi-colour 3D print) and in 5.2.5.3. (multi-material 3D print) should in effect be seen as expository design, rather than finite and complete propositions/redesigns of the curtain wall detail outlined in 1.6.4. A further reason for their expository, as opposed to finite nature, is that a large part of the computational process model proposed is a framework that similarly to a piece of pseudocode can acquire higher specificity when deployed in practice. The 3D prints in effect helped verify some of the assumptions made during the process, but could only form finite and usable pieces when the model proposed was made technically accurate, and appropriate manufacturing techniques eschewed the current unavoidable retort to physical representational materials.

6.5. Mutability of the Proposed Process Model

Correspondingly, in terms of the mutability of the output of the PhD, which is the aforementioned process model (outlined diagrammatically in 6.2.), this consists of parts that are technically descriptive in nature, (Visualisation and Fabrication parts in Figure 100) and others that provide a series of steps and principles that can be taken as a starting point in order to research, design the containing vessel, set-out, run, and terminate the simulation (Fusion Mould Design, Research, Simulation Set-out, Material Blending Simulation, and Simulation Stop in Figure 100). The latter parts in effect are not technically specified and can be made much more definite in practice. This is the case because although there are some parts of the process models that require architectural expertise, there are others that are scientific in nature.

6.5.1. Fusion Mould Design

For instance, taking the Fusion Mould Design part as an example, this consists of three conditions namely that *a.* 'the form and orientation of the mould and the material compartments should be informed by the properties of the substances to be fused', *b.* 'the formal characteristics of the mould should follow the ones from visible material scales (as opposed to micro-scales) of FGM in nature', and that *c.* 'the mould dimensioning and proportions should also be dictated by the function and positioning of the multi-material within an overall multi-material construct.' Condition *c.* concerns an architectural consideration of whether the multi-material to be designed is a facade, or a floor segment, or a much more complex interface between facade, structure, and floor/ceiling. Conditions *a.* and *b.*, however, are basic guidelines that in effect can be made much more scientifically and technically substantiated. As briefly outlined in 3.3.5. for instance, the enthesis condition is a vast independent research topic that would require collaborations with specialists (biologists, material scientists, and structural engineers) in other disciplines for it to inform the design of the mould on a more accurate technical level. This is because the outlined interdigitation and shallow attachment angle principles are effective with fibrous, fibrocartilaginous and osseous sub-materials. These being replaced here by aluminium, alumina, and glass, and a different loading condition applied to the resulting multi-material, means that extensive research would need to be performed in order to verify that the two aforementioned principles would work equally well with these different sub-materials.

6.5.2. Research

Additionally, looking into step 8. of the Research part in Figure 100, this suggests that the loading condition on the multi-material segment should be aligned with the force generated during manufacturing of the FGM. As described in 6.3.2.4., however, this would only be the case when the multi-material entity that one would work with could not be directly 3D printed. In the opposite case, step 8. should in effect be omitted. Furthermore, according to step 7. there needs to be a calculation of the anticipated structural loads on the segment, which is something that was partially performed in 3.3.7.1. (involving a stress and a displacement analysis). The claim in effect was that the resulting blend in 3.3.9. exhibited an alumina distribution that matched the displacement analysis pattern. Examining the stress analysis distribution on the other hand, an opposite loading pattern to the displacement was exhibited. Alumina would therefore need to be distributed (through the use of appropriate daemons in the simulation) in the multi-material so as to cover these opposing conditions, at the same time corresponding to the various other structural, wind load etc. forces developed in the connection. Alumina was chosen due to its compatibility with both glass and aluminium, but the critical question would be whether it would work equally well with the anticipated displacement and stress loads. Again, here, there would need to be consultation with materials scientists and structural engineers for an in-depth technical understanding of sub-material to structural behaviour correspondence.

6.5.3. Simulation Set-Out

Regarding the Simulation Set-out part in Figure 100, the separation of fixed and adjustable parameters is related to the fact that some of these (such as gravity) are fixed universal values, while others like the container shape (having emerged from all the above considerations) are scientifically derived and effectively cannot be changed. The adjustable ones that concern the size of the container, its orientation and proportionality between its parts, suggest that the mould can be scaled up or altered, which, however, is something that again needs to be technically verified. Over-scaling the container, for instance, could result in a different structural behaviour to the one anticipated, which in effect would necessitate strict criteria (that could be formed again through consultation with engineers) that would allow the designer to set out the limits of this scaling operation.

6.5.4. Simulation Stop, Visualisation and Fabrication

In terms of the parts that follow the Material Blending Simulation, the Simulation Stop part, which effectively consists of the criteria that have been established as to what forms a 'good mix', will be discussed in 6.7. The Visualisation and Fabrication parts that come after are technically specific and in effect have less of the mutability and adjustability that the initial parts of the process model exhibit. Having said that, in the incessant development and advancement of computational tools that designers are working with, the use of commercial and widely accessible CAD tools in the workflow, has been an attempt to introduce a set of basic boundaries in an incessantly advancing world of technological and computational innovation. Typically, what is considered novel today will be obsolete tomorrow, and it therefore ought to be mentioned that the specificity of these latter parts could also be stripped down to the level of pseudocode that could be much more malleable in nature and adaptable to CAD software developments.

6.5.5. Gradual Degree of Mutability

Overall, the process model transitions from a backbone of a set of parameters (namely found in the Fusion Mould Design, Research, and Simulation Set-Out parts) that the multi-material designer using simulations ought to account for (which can be 'reinforced' with further scientific precision), to the technically determinate output methods of Visualising and Fabricating fusion. Equally importantly, and going back to the aforementioned incessant CAD software advancement, as described in 4.3.7.12. the earlier parts of the process model could be reconfigured, with the mould design taking place while the material fusion simulation is running. In this alternative workflow, one observes the impact that the vessel's form has on material fusion, adjusts the form accordingly, and re-runs the simulation repeatedly until the desired output is achieved.

Ultimately, this is a flexible, partially re-adjustable model, parts of which can be made increasingly technical or decreasingly abstract. This mutability has been deemed necessary in order to preserve the relevance of the tool in an evolving environment of technological, scientific, and architectural evolution.

6.6. The Link Between Theory and Design

In terms of the cognitive and materialist discourse (namely the conceptual blending theory introduced in 4.2.) and how this informed the development of the design workflow, this departed from the standard practice of applying a pre-given theoretical model to a design procedure.

More specifically, regarding the sequence of how the various practical, design, and theoretical aspects of the thesis inform one another, the starting point of the research, as stated in 1.2.7., 1.2.8., and 1.3.1., has been the inevitability of the gradual assimilation of multi-materiality in architecture and building construction. With this as the starting point, the main focus to the PhD has been the proposition of an alternative method of designing with functionally graded materials in anticipation of the aforementioned assimilation. Bearing this in mind, the theoretical aspect in the thesis was used in a complementary manner to the design research, and was namely utilised to elucidate and acquire an in-depth understanding of the cognitive processes taking place while designing with multi-materials in the computer. In other words, theory was deployed as an analytical tool, rather than a pre-existing and self-supported piece of knowledge that was targeted towards design applicability. In addition, due to the nature of the subject matter (which as briefly mentioned in the abstract operates within an unruly and wilful material domain devoid of any theoretical or tested and applied design precedents) an ongoing endeavour during the course of the PhD research has been to identify an appropriate theoretical discourse (if any) that could correspond to this newly-emerging design field. As mentioned, when this theory was identified it became instrumental in explicating key aspects of the design in attempt to shed new light in the thought processes taking place in the background and while working with this new type of material. Theory in effect did not precede design, but rather design preceded theory, or design was in search of an appropriate theory, which was found in the cognitive theory writings of Fauconnier and Turner. The argument and research question that co-developed from this way of researching were directed towards the reconsideration of the precepts of form being independent from materiality, and of theory preceding application, in its turn linked to the idea of top down architectural authorship.

6.7. Design and Theory Evaluation Methods

In terms of any methods that could be applied for evaluating the interdisciplinary inputs into the design, as well as the designs that were generated during the process model described, these had primarily to do with the recognition of a specific pattern in the fusion area between the materials. More specifically, as discussed in 4.3.7.10., there is an extensive literature in materials science of the micro-characteristics of graded materials that includes written and diagrammatic descriptions, as well as images of FGM samples. An analytic description and a diagram by Myiamoto et al. (1999, p.42) were used in this instance to pin down the graded region features that a designer ought to strive towards. Other instances were also illustrated of conditions where micro-dispersal is too extensive leading in alloy-like materials, or ones where dispersal is too limited to form a gradient. In both cases it is anticipated that the properties of the resulting materials would be altogether different to an FGM. An alloy would essentially be a unique material, while in the case of limited dispersal this would imply the existence of an abrupt transition between the two sub-materials, in its turn leading to the same problems found in mechanical or composite connections (described in 1.2.6.).

6.7.1. Main Evaluation

The main evaluation method in effect involves a pattern recognition process, during which the designer can discern whether the gradient characteristics are the same, or alternatively are similar to the ones formulated by Miyamoto et al. (1999). Correspondingly, this implies that there is a shift here from the arrangement of linear elements, and the use of proportionality and distance ratios between parts in order to generate an adequate aesthetic result (namely in the design of envelopes), to recognising the formation of adequate gradients in material mixes. This is something that has been outlined in point *h.* (concepts of composition previously based on discrete geometric elements will effectively have to be rethought) in 1.3.1., and although belonging to a different discussion to the present thesis (one of aesthetics and composition) at the same time illustrates the change in design perception. Beyond making sure that the envelope attains certain functions (such as allowing access to views and light, being structurally adequate etc.), the previous composition-driven organisation of the facade in this case is superseded by the sufficient fusion of sub-materials and formation of 'appropriate' gradients.

6.7.2. Good or Plausible Models

In terms of the ability to differentiate between a good and a merely plausible model, this is a more difficult challenge to the multi-material designer, even more so in light of point *d.* (the margin for error will decrease) that was made in 1.3.1. The argument that was made previously is that gradients are by their nature more 'forgiving' than discrete components, which demonstrates this difficulty of discerning between a successful or plausible output. At the same time, bearing in mind the aforementioned description of graded micro-dispersal, as well as the definition of the term gradient (in the Merriam-Webster dictionary) as "1 a: the rate of *regular* [emphasis added] or *graded* [emphasis added] ascent or descent"[70], the key objective is the maintenance of a continuous and progressive change in material consistency across the area of fusion. In effect here, the multi-material designer trained in pattern recognition and with an acute ability to discern smooth gradation would classify FGM exhibiting this regularity in transition as 'good' models, while the further the designed multi-materials would deviate from this (for example consisting of areas of more abrupt transitions) the least plausible the model would become.

6.7.3. Theoretical Evaluation

Moving on, in terms of the theoretical criteria against which the hypothesis that material and form are inseparable in the workflow proposed (as outlined in 1.7.1.) was made, these have

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70 and "2: change in the value of a quantity (such as temperature, pressure, or concentration) with change in a given variable [emphasis added] and especially per unit distance [emphasis added] in a specified direction."

been borrowed from cognitive theory and more specifically by Fauconnier and Turner (1998) and Hutchins (2005). In terms of the former, Fauconnier and Turner (1998) provide extensive descriptions of what conceptual blending is, the types of integrative networks that the human mind constructs on a subconscious level to perform complex, blended mental operations, as well as a comprehensive set of examples that illustrate their theory. In effect, the structure of a single-scope network was used to map out the conceptual process behind the design of the mould (in 4.2.8.) and of a Y[6] network multiple blend behind the visualisation of the multi-material (in 5.1.6.). The employment and logical sustenance of these formed a verification of the hypothesis that conceptual blending is involved in the design process. This is because the structure and set of relations in Fauconnier and Turner's writings were unchanged and were logically supported when filled in with the variables of the process model. This came to demonstrate *a.* the designer's thinking, on a deeper, subconscious level and *b.* the fact that when blending materials in the computer, one deploys a specific kind of cognitive process that similarly involves blending, but on a mental level (consisting of separate mental spaces that are fused together to generate emergent meaning). Consequently, to be successfully performed, *material blending requires mental blending*.

Additionally, on a more practical level, the main claim has been that although one is at times working with material-less B-Reps, through the criteria outlined in terms of what forms a material anchor for conceptual blending (Hutchins, 2005), it was proved that the same type of blending occurs during certain instances of the design process (in 4.3.3.). One is effectively using the B-Rep as an anchor onto which to project conceptual material data. In projection, this is due to the shortcomings of present day CAD software that omit materiality (let alone graded materiality) from their computational structure and as a result one must employ these cognitive processes to fill in the mental and procedural gaps generated by these shortcomings.

Going back to the theoretical sub-objective of the thesis as outlined in 1.7.1., it has been argued that form and materiality cannot be sustained in isolation at any part of the process model. This is the case as materials are always present either in virtual form in CAD, or in the form of conceptual materiality (as posed in 4.3.2.), or as physically output (albeit representational) multi-materials. Each of these kinds effectively gets projected on, precedes, or co-evolves with form.

6.8. Further Development

In conclusion, and looking towards potential future development of this PhD research, the opportunities offered have to do with the possibility of conducting further investigations into the structural capabilities of the proposed functionally graded material connection. Additionally, another area of development would be to conduct further research into the fabrication of the connection using non-representational sub-materials (i.e. in alumina, aluminium, and glass), and once manufactured, the evaluation of the connection's optical and aesthetic qualities from an architectural point of view.

The main constraint in achieving this currently, is the lack of availability in a 3D printable form of the sub-materials that were used in the multi-material. The way around this issue would be to either wait until these materials and the relevant 3D printing technologies became available, or alternatively to conduct further research in order to identify the appropriate industrial equipment (centrifugal casting moulds etc.) needed for their manufacturing. As mentioned, collaboration with material scientists, and structural engineers would be needed to resolve this technical challenge.

Overall, the worthwhileness of this research effort and of any further development, has to do with the problems associated with curtain wall glazing that were outlined in the introduction, namely in 1.6.2. Overcoming the considerable technical problems that are currently posed on a material and manufacturing level, could have immense impacts in reducing the environmental hazards, inefficiencies, redundancies and assembly problems associated with this type of building envelope. The outcomes would be the abolition of the costly, redundant and toxic-waste producing processes deployed in manufacturing curtain wall components, as well as the radical decrease in the total number of materials used in the envelope that would effectively be replaced by a mere three materials, fused together and 3D printed in one go.

6.9. A Multi-Material Integration Roadmap

Projecting this further, on a building design level, according to Kwinter (2010), the three most defining buildings of the twenty-first century so far, have been Reiser and Umemoto's Shenzhen Bao'an International Airport and O-14 Office Tower in Dubai (Figure 101), as well as the Taichung Metropolitan Opera House by Toyo Ito & Associates (Figure 102). This is as all three of them:

> "deploy an anticlassical, nonmetaphoric, nonanthropomorphic approach to the perennial skeleton theme, in which structural parti is no longer conceived as torque- and load-bearing rigid members, interconnected with joints and relays to form a cooperative self-sustaining whole; in other words, as derivations of post-and-lintel tectonics, abetted with performing skins and musculatures. On the contrary, the structures are conceived "of a piece," as unitary, essentially componentless entities [emphasis added] that manage and distribute forces in the manner of a single osseous structure or bone." (Kwinter, 2010, p.40)

These buildings in effect, can be said to be already paving the way for a new example of material continuity and seamlessness that is merely the opening chapter in what is to follow.

It is at same time very likely that although the built output is ground-breaking, the design process that led to the creation of these three buildings followed the hylomorphic model that this thesis has argued against. Nevertheless, it can also be anticipated that the workflow presented here, i.e. the use of material simulations[71] (applied to the curtain wall segment re-

71 The only built example identified so far, in which a material simulation (generated in Real-

‘design’), will at some point in the near or remote future be applied to the facilitation of a fully materially graded building.

On a practical level, the series of steps that need to be taken for graded-materiality to be assimilated on a building level are:

1. *The expansion of the material palette* that can be used in multi-material 3D printing, beyond the current limited range of plastics. The objective in effect would be to achieve the 3D printed fusion of structural materials such as steel and concrete, optical ones such as glass, insulating ones, flexible materials that allow operability of components such as windows, as well as materials for finishing. The fusion of these (or alternative ones that have the same properties), however, poses a significant technical challenge.
2. *The scaling up of multi-material printing*. This is now the case with singular materials such as concrete, and other instances like the magnesium chloride bound sand material used in the D-shape additive manufacturing technology. The objective would be to incorporate the above-mentioned expanded multi-material palette in existing large-scale 3D printing.
3. *The subsequent fabrication of building segment multi-material mock-ups* for testing and evaluation. These would be necessary in order to conduct structural loading tests, evaluate the amount of light penetration and potential distortion of the transparent sub-segments, as well as to evaluate the aesthetic result, among other possible tests.
4. *The development of methods for the targeted amendment of multi-material parts* in areas where replacement sub-materials are required. Tectonic construction allows (for the albeit messy) removal of discrete parts and the replacement of these by ones that are new. In a fused construction scenario, this cannot be the case and therefore the relevant capability is required for the 3D printing and ‘welding’ of graft sub-materials onto and/or within a larger multi-material construct.
5. *The 3D printed construction of a multi-material building* (as opposed to multi-material segments that are assembled together tectonically, as outlined in 3.).

Flow) was used in the design process, is the New Foyer and Adaptation of the Building Academy in Salzburg, Austria by Soma Architects (Gengnagel, Kilian, Palz, and Scheurer, 2011) (Figure 103). In a research article discussing the design process, however, although the architects mention the existence of parameters such as viscosity, density, and surface tension, as well as the use of attractor forces, the simulation is used merely as a pattern generation tool in order to achieve a large number of openings in the structure. Eventually built in concrete, a remark here is that there could have been an attempt to input the properties of the material in its liquid state, in order to simulate and predict its rheological behaviour during construction, also avoiding that way a formally-biased approach.

Placeholder

Figure 101: The O14 Office Tower, by Reiser and Umemoto. The continuous concrete exoskeleton provides the primary vertical and lateral load support for the building, freeing up the internal space from columns and enabling the reduction in depth of the floorplates and in the overall size of the lift core.

This can be seen as the last hurdle that once overcome will allow for multi-material construction to become mainstream practice.

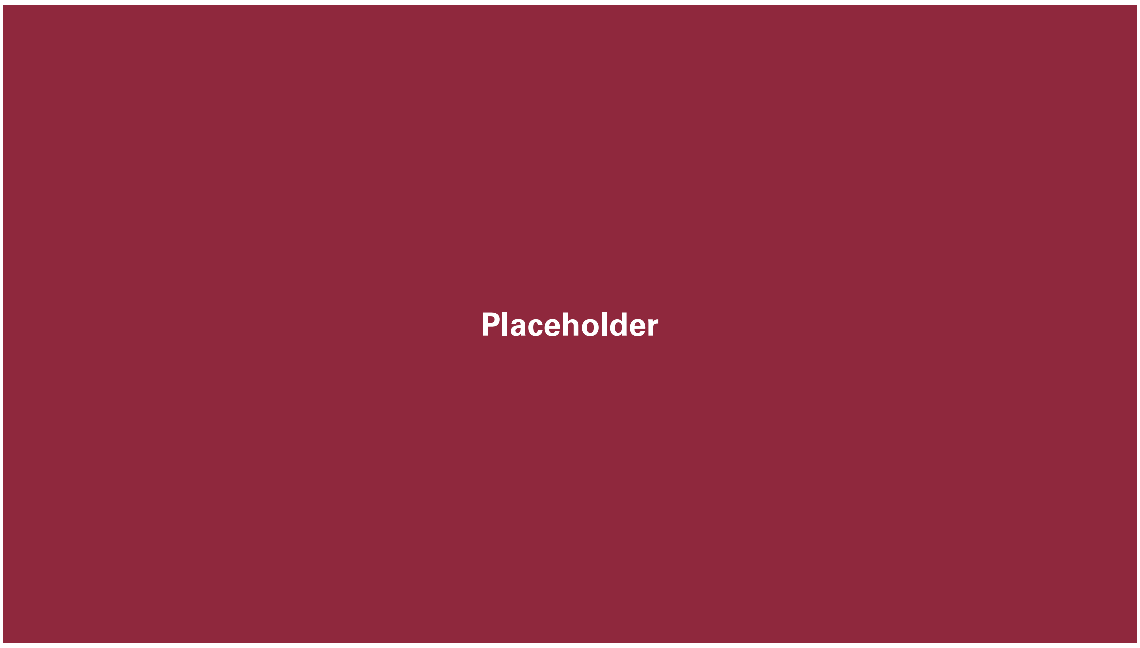


Figure 102: Physical Model of the Taichung Metropolitan Opera House, by Toyo Ito & Associates. The main feature of the building is its continuous steel and shotcrete structure that simultaneously forms the walls, ceilings, and floors.

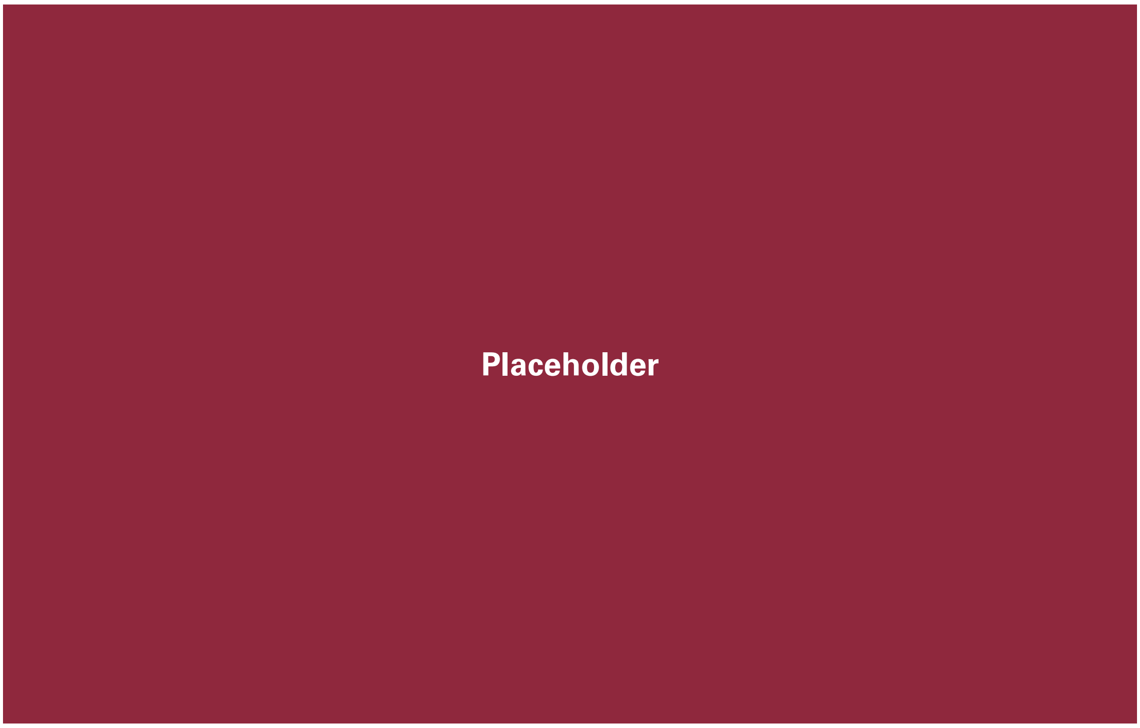


Figure 103: Interior View of the New Foyer and Adaptation of the Building Academy in Salzburg, by Soma Architects, showing the concrete structure derived from a fluid simulation.

Going back to modernism and the international style, according to Hitchcock and Johnson (1997, p.82), "one of the surest signs of the real existence of a style of architecture is the creation of a fixed type of window detail." This research has strived to rethink anthropocentric ideas and the synonymous to these, notion of style. At the same time, however, the above quote comes to illustrate that this can potentially be the beginning of an investigation that is going to occupy architects, designers, as well as design and material culture theorists very soon. In anticipation of this, the PhD research outlined the expected changes that will occur as a result of multi-material integration in architecture, proposed a new process model for designing with multi-materials, examined the mental processes taking place during this workflow, proving in effect the enmeshed connection of form and materiality, and lastly outlined a roadmap towards the gradual assimilation of multi-materiality in architecture.

GLOSSARY

Agency: The capacity that an 'actor' has, to act within an environment.

Agency (Force)- External: A user-assigned forcefield that affects the behaviour of a fluid in a virtual simulation. An example of a physical equivalent is a magnetic force affecting the behaviour of a ferrofluid.

Agency (Material): The propensity of a material to acquire certain formations based on its chemical composition, and/or the possibilities that a material affords to be interacted with.

Anthropocentricism (or anthropocentrism): A belief that places the human as the most important entity in the world.

B-Rep or Boundary Representation: A method of representing a virtual form using external limits in a Computer Aided Design (CAD) environment.

B-Rep Anchor: The use of boundary representation objects to project and stabilise conceptual material ideas on a directly perceivable computer element.

Composite Materials: Materials that consist of two or more substances that when combined acquire altogether different physical or chemical properties. The combination occurs either in the form of laminates (layers of materials that are glued together) or alternatively aggregates, with none of these, however, exhibiting gradation between the constituent materials.

Computational Blending: The mixing of two or more materials virtually, in a computer simulation software.

Conceptual Blending: The subconscious cognitive operation taking place in the human mind, of integrating different mental spaces in order to give rise to emergent meanings.

Conceptually Blended Design: The design methodology proposed in the thesis, in which material information is conceptually and mentally blended with formal considerations. This blending is inherently linked to the use of functionally graded materials in the design process.

Conceptual Materials: Materials that are thought of or perceived in one's mind.

Daemon: A virtual forcefield that can be user-assigned in a simulation environment that is external to a particle system, and affects the behaviour of particles that fall within its field of influence.

Emitter: The source of particle emission that controls the behaviour, position and movement of particles in digital 3D space.

Enthesis: The point of connection between muscle, ligament and bone in the human body that consists of a functionally graded material.

Extended Mind Hypothesis: The thesis which holds that one's mind and cognitive processing are not confined within one's body but extend out into the environment.

Fluid Values: User input parameters, which can be measured in scientific units (kilogram per cubic metre for the density of a fluid for instance) and that can be assigned in a simulation software to specify the behaviour of a fluid.

Fluid Properties: User input parameters, which are not measured scientifically (but in units that are specific to the computer program) that can be assigned in a simulation software to specify the behaviour of a fluid.

Functionally Graded Materials or Multi-Materials or Fused Materials: Materials that consist of two or more substances that are fused together continuously over a single material volume, and from substance A on one end, an equal amount of substance A and B mixed in the centre, and substance B on the other end.

Fusion: The mixing of two or more materials and the formation of visible gradients at the area of their connection.

Fusion Compatibility: Whether two or more substances can mix together based on their chemical properties.

Hylomorphism: The Aristotelian philosophical theory that claims that being is made of two constituting elements, matter and form. The term is used in the thesis as formulated by Tim Ingold, who defines hylomorphism as the imposition of preconceived formal attributes on what is seemingly inert matter.

Intrinsic Material Properties: The quantitative and scientifically measurable properties of a material. These can consist of acoustical, atomic, chemical, electrical, magnetic, mechanical, optical, and thermal properties among others. The ones dealt with in the thesis are mainly mechanical, and chemical.

Invasive (or Intrusive) Forces: Forces generated using a solid apparatus or tool that coerces form upon two or more materials that become attached together in a non-gradient manner. An example is the process of accumulative roll bonding that generates an abrupt intermetallic compound layer that holds two solid materials together.

Lineament: The original use of the word was in the first book of De Re Aedificatoria (On the Art of Building) by Leon Battista Alberti and denoted a series of mentally constructed lines devised in the architect's intellect that were effectively drawn up to be conveyed to builders. This is a similar concept to the separation of form and matter and the imposition of the former on the latter, as defined by Tim Ingold.

Material Engagement Theory: The thesis that the isolated, 'internal' mind is extensive and involves materials and objects as part of cognitive processing.

Material Gradients (Physical and/or Digital): The formation of a visibly graded area at the point where two (or more) materials have merged together. The middle part of this area typically consists of the two materials mixed in equal parts, with this ratio gradually changing towards a uniform condition on either end of the fused part.

Material Simulation: The imitation of material behaviour in a digital environment.

Materialism: The philosophical position that considers matter to be the fundamental entity that all mental processes and consciousness itself result from.

Materially Anchored Conceptual Blending: The cognitive strategy of employing material elements for projecting conceptual structure on these entities.

Materially Projected Boundary Representation: The mental projection of material characteristics on a Boundary Representation or B-Rep. This involves imagining the presence of various materials on the otherwise typically immaterial computer element.

Mental Space: A theoretical construct devised by Gilles Fauconnier that is essentially a cognitive assembly that one constructs while thinking and talking, in order to generate meaning. This assembly is not a representation of reality, but an "idealised cognitive model."

Mould (or Container): The containing (B-Rep) vessel required for simulating the mixing of liquid materials in the computer. This is the digital equivalent of the jar component in a blender (the kitchen appliance).

Non-Contact (or Non-Invasive or Accelerating) Forces: A non-solid, non-fluid forcefield within the influence of which, the atoms and molecules that a material is composed of find particular arrangements in space that are brought forth by the combination of the influence of the forcefield and the properties of the material itself.

Partial Accuracy: The hypothesis that a full attribution of scientific and measurable material properties is not required for achieving adequate material fusion that closely resembles physical reality.

Particle: A computer graphics point object that is deployed in large numbers to simulate fuzzy physical phenomena (that have vague i.e. non-clearly defined boundaries) in the computer.

Particle Mesh: With commercial CAD software employing geometry-based elements that are manipulated to generate a design, particles need to be converted into a geometry for further editing purposes, and for visualisation and fabrication. This conversion is done by applying a computer mesh that forms the outmost boundary of the blended particles.

APPENDIX

External and internal views of the multi-material 3D print.

Dynamic Simulation
Gravity : 0.0 (def 9.8)
Viscosity : 0.0
Friction : 0.0
Damp : 0.0

Self Attraction And Repulsion
Self attract : **-400.0** (def 0.1)
Self repel : 0.1
Equilibrium value : 150.0 (0.5)

Self attract : **-300.0** (def 0.1)

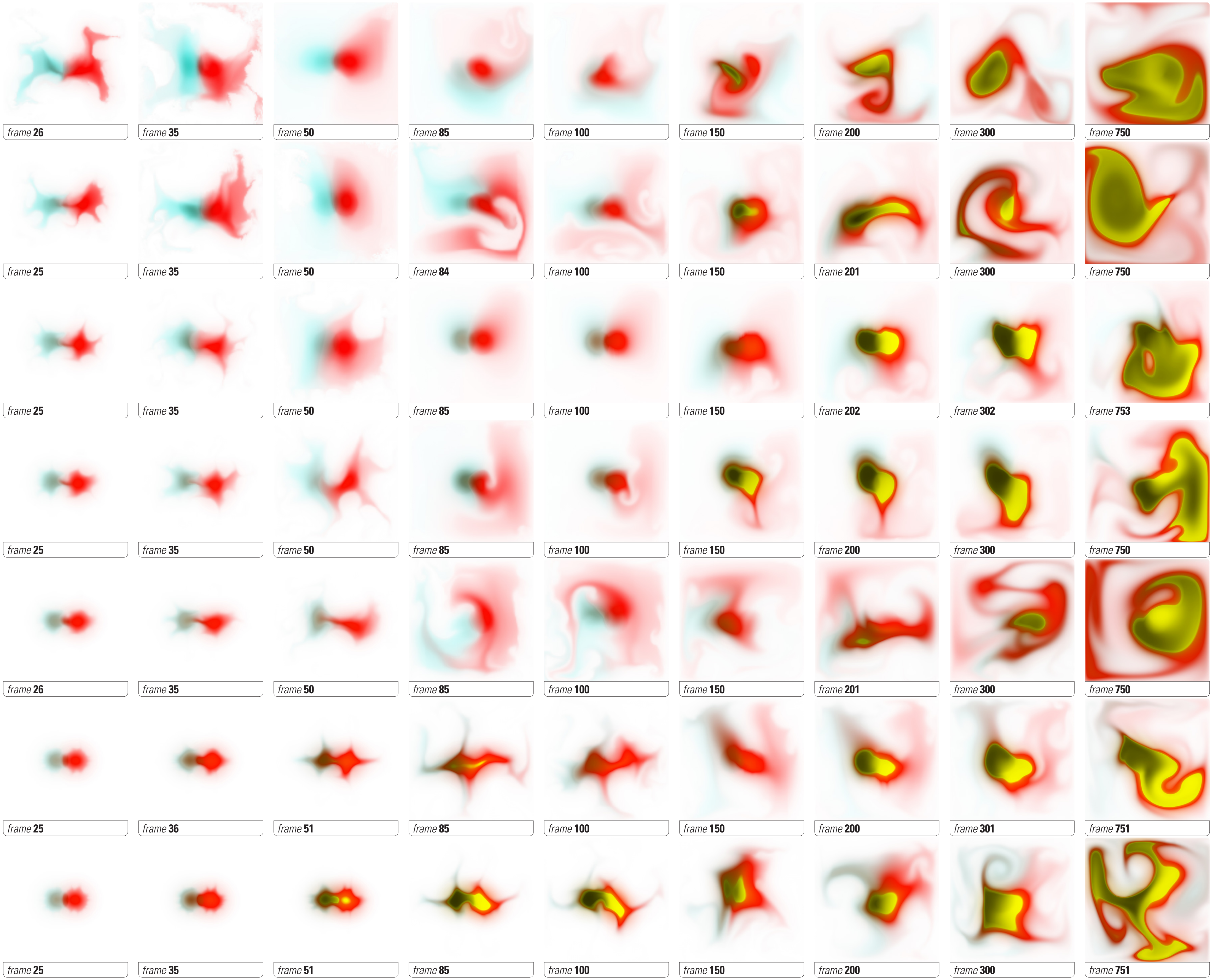
Self attract : **-200.0** (def 0.1)

Self attract : **-150.0** (def 0.1)

Self attract : **-100.0** (def 0.1)

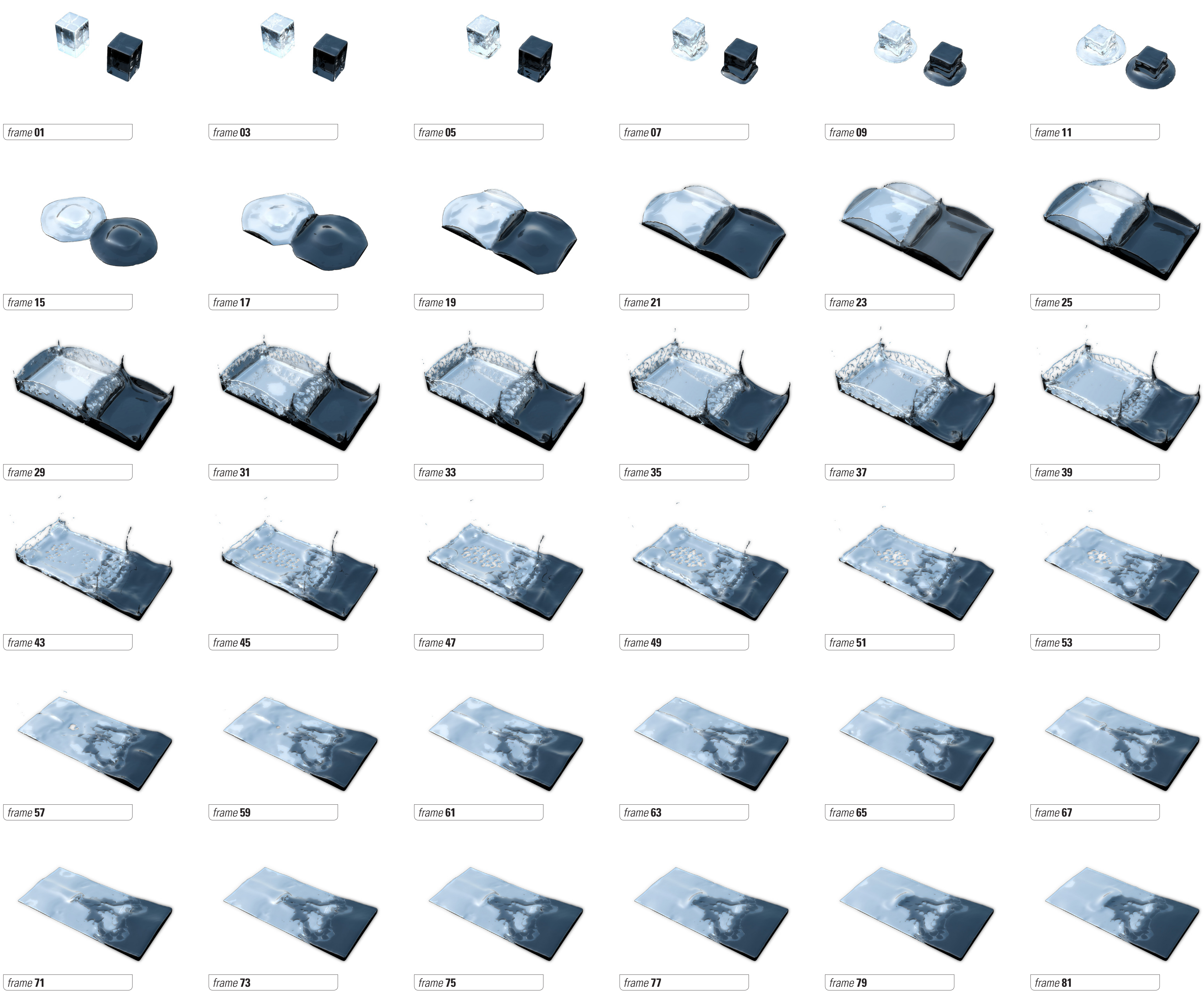
Self attract : **-50.0** (def 0.1)

Self attract : **-25.0** (def 0.1)

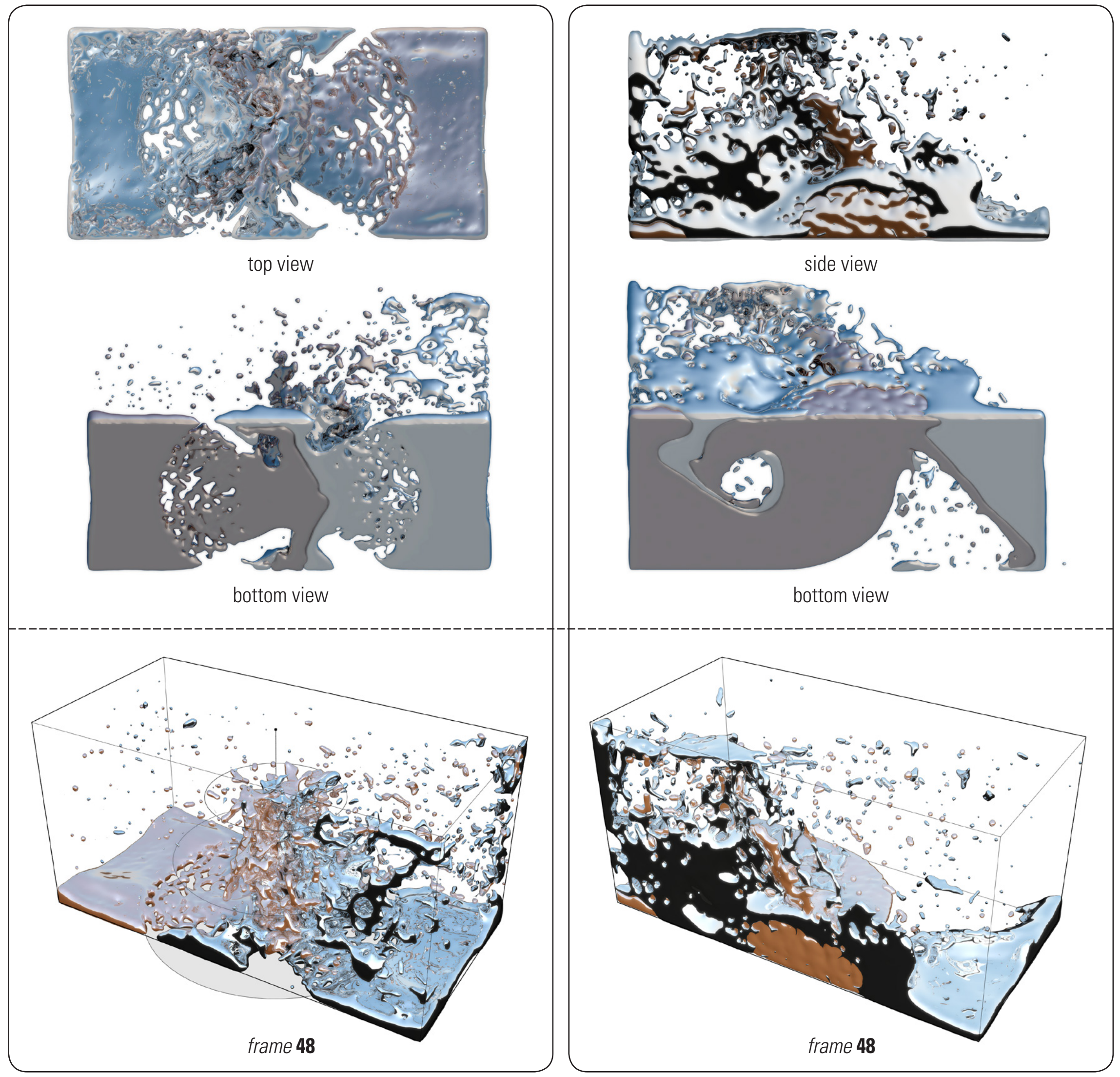


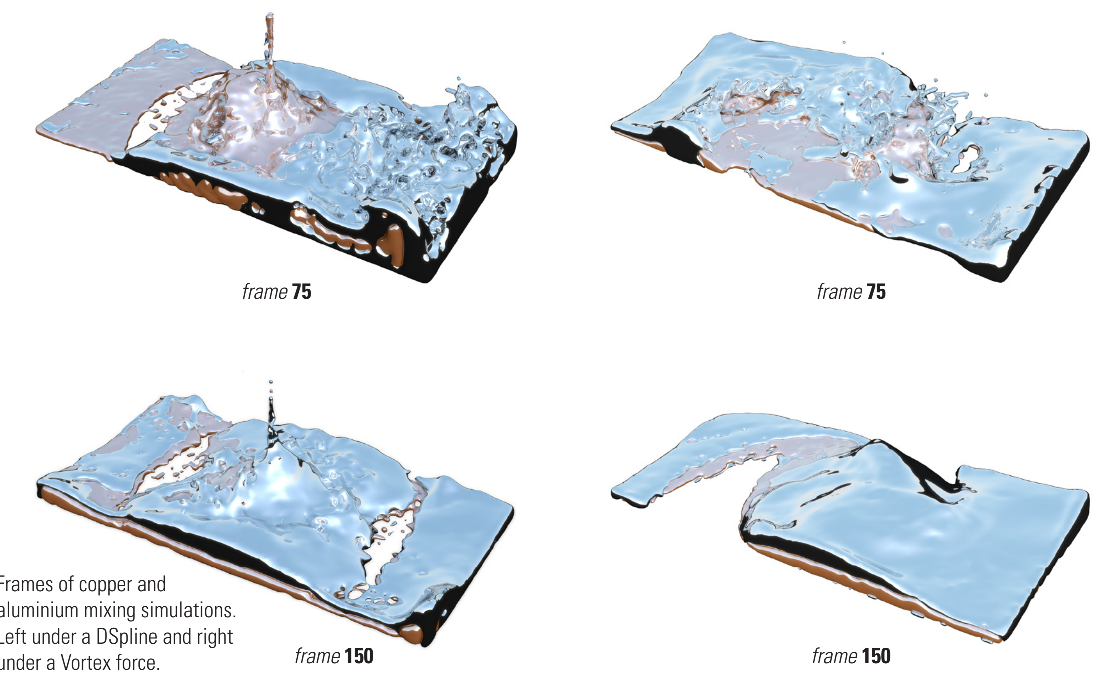
Two emitter fluid simulations, showing different arrangements attained under a variety of self attraction settings. The objective was to achieve the formation of gradients. Frame 50 in the third row was presented in 3.1.2.4.

Particles
Type: Liquid
Resolution: 1.0
Density (water): **1000.0 kg/m^3**
Density (oil): **885.0 kg/m^3**
Int pressure: 0.5
Ext pressure: 1.0
Viscosity (water): **0.001 Pa·s**
Viscosity (oil): **0.195 Pa·s**
Surface tension: 200.0
Interpolation: None
Compute vorticity: No

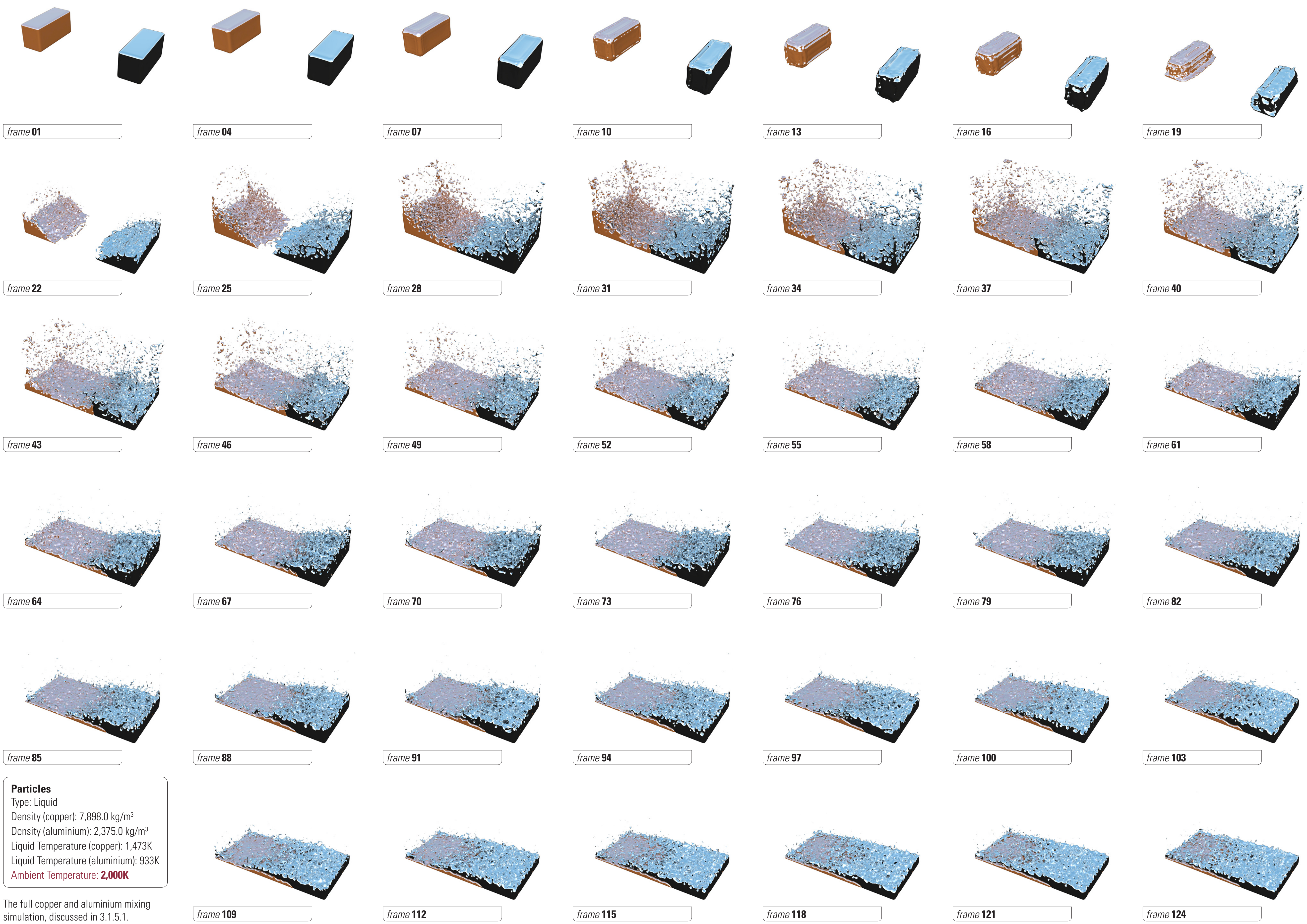


The full oil and water mixing simulation, discussed in 3.1.4.

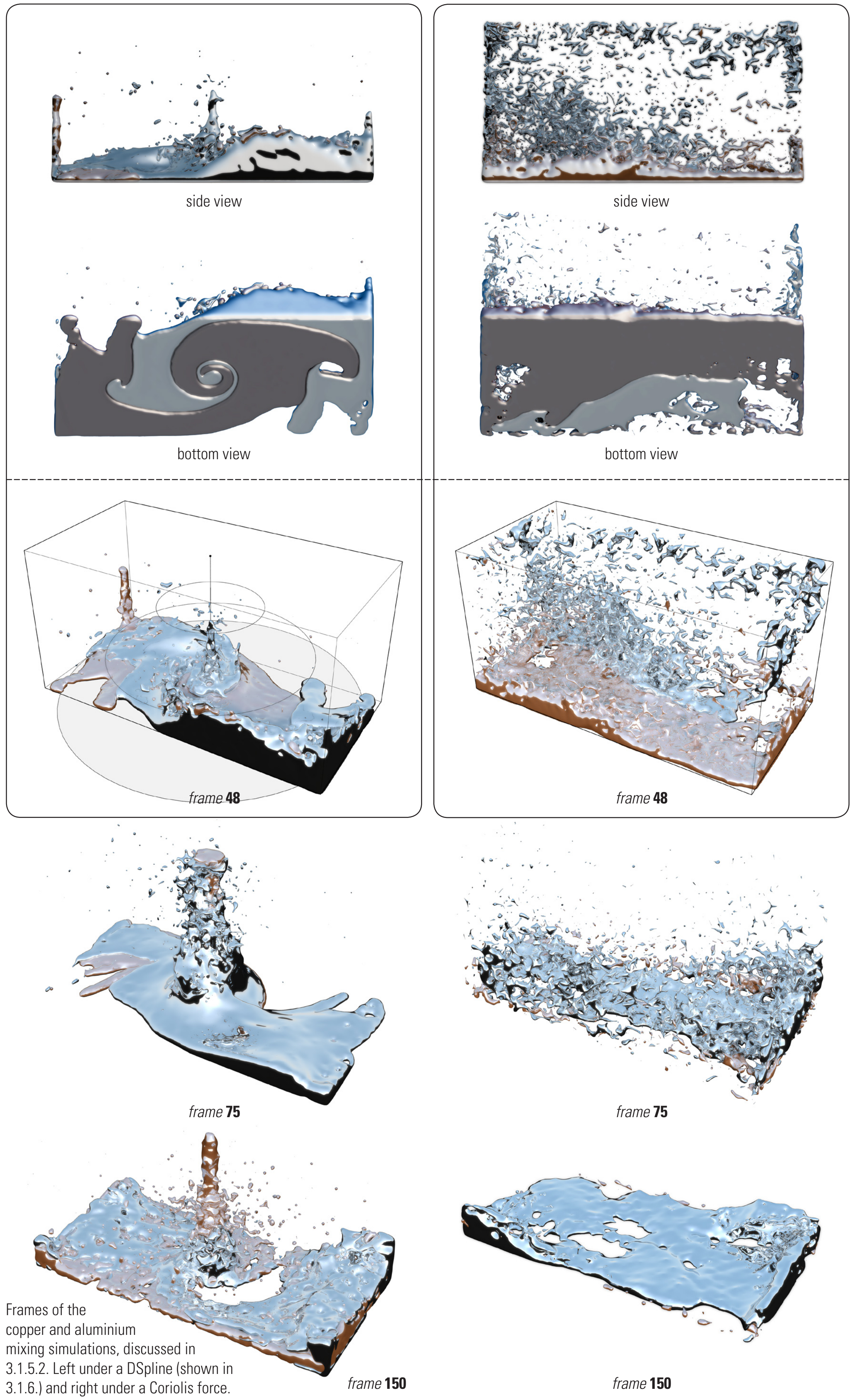




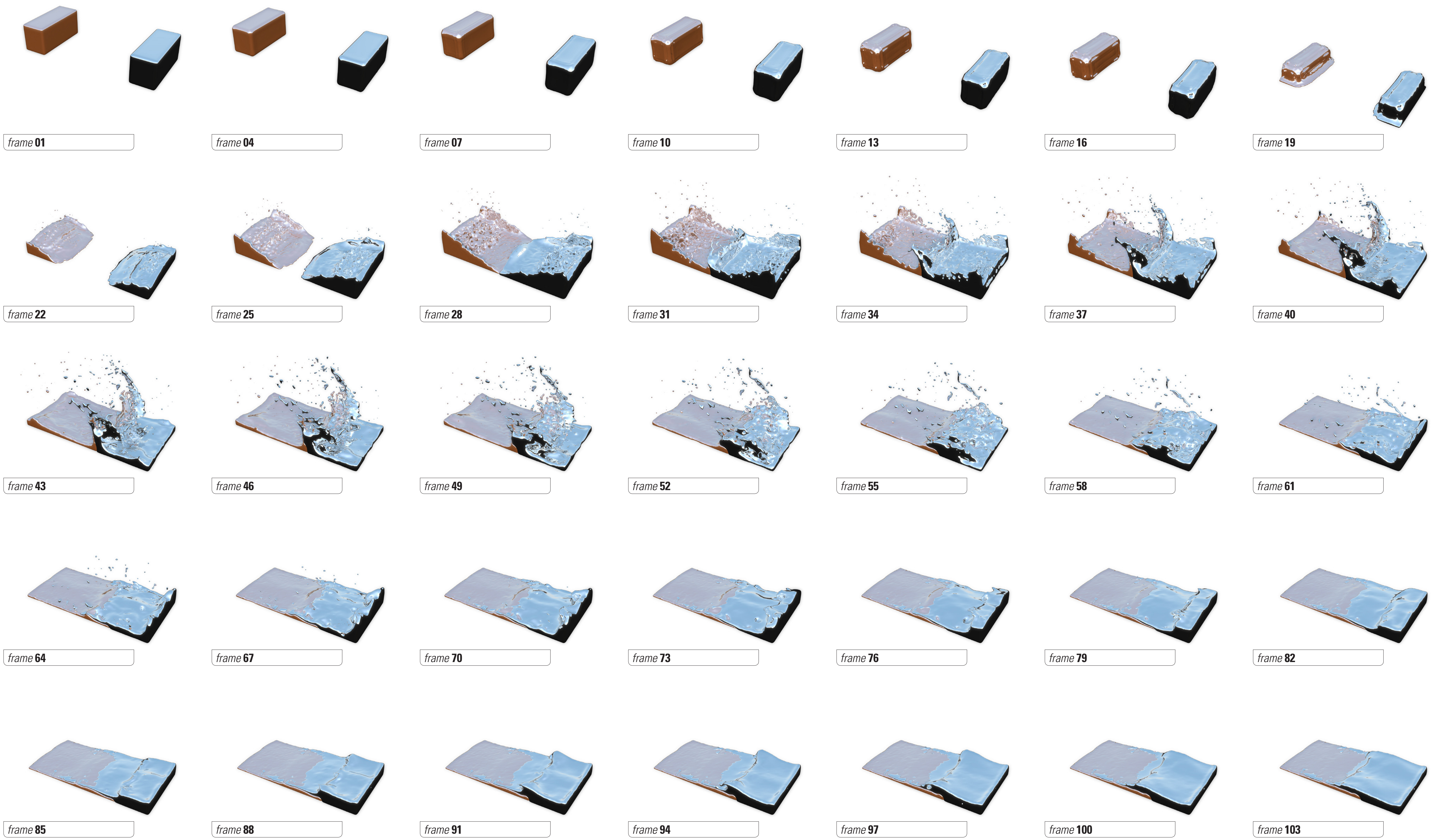
Frames of copper and aluminium mixing simulations. Left under a DSpline and right under a Vortex force.



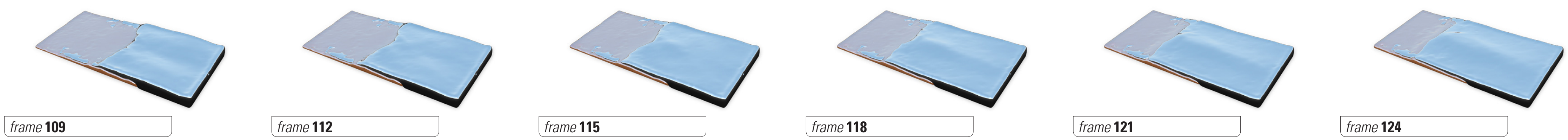
The full copper and aluminium mixing simulation, discussed in 3.1.5.1.



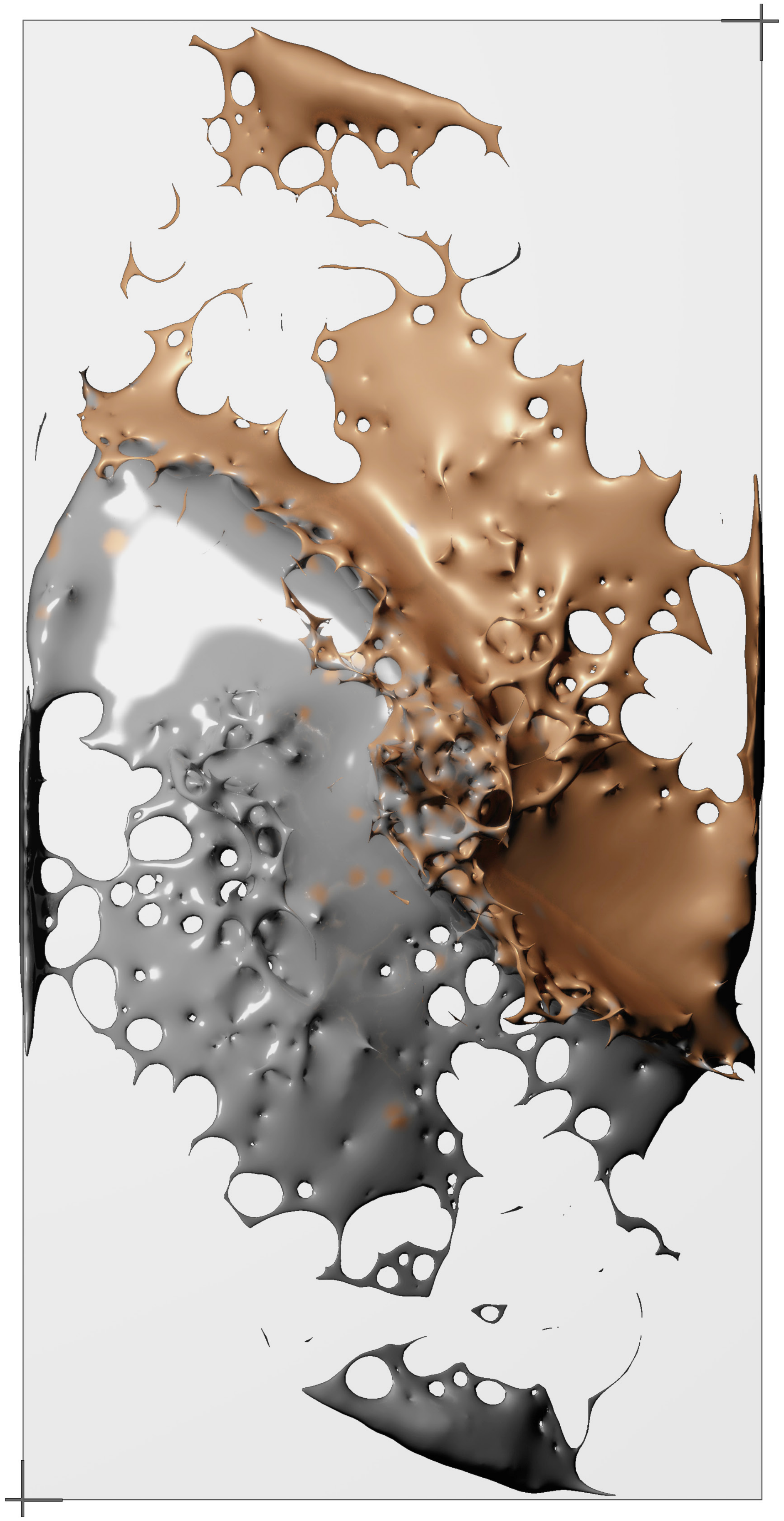
Frames of the copper and aluminium mixing simulations, discussed in 3.1.5.2. Left under a DSpline (shown in 3.1.6.) and right under a Coriolis force.



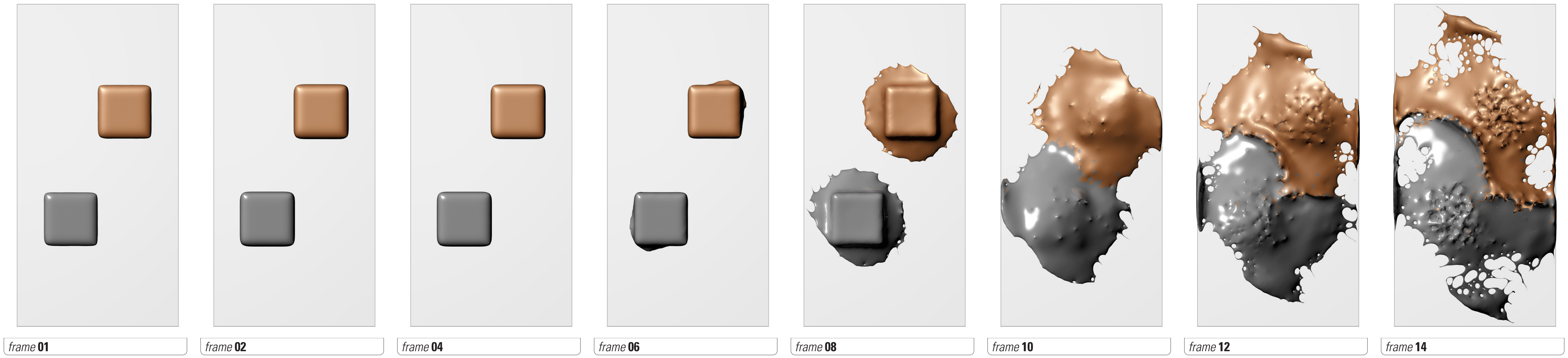
Particles
Type: Liquid
Density (copper): 7,898.0 kg/m^3
Density (aluminium): 2,375.0 kg/m^3
Liquid Temperature (copper): 1,473K
Liquid Temperature (aluminium): 933K
Ambient Temperature: **400K**

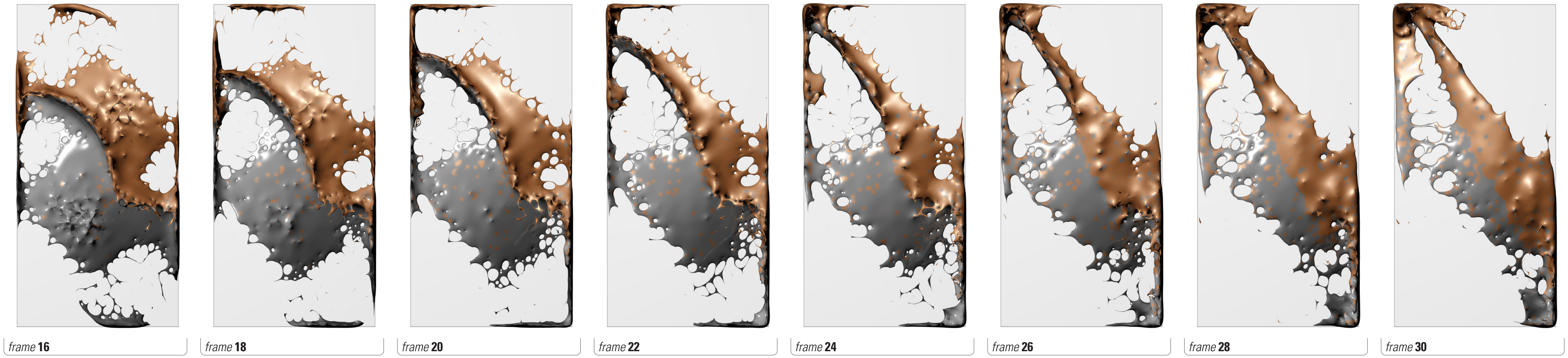


The full copper and aluminium mixing simulation, discussed in 3.1.5.1.

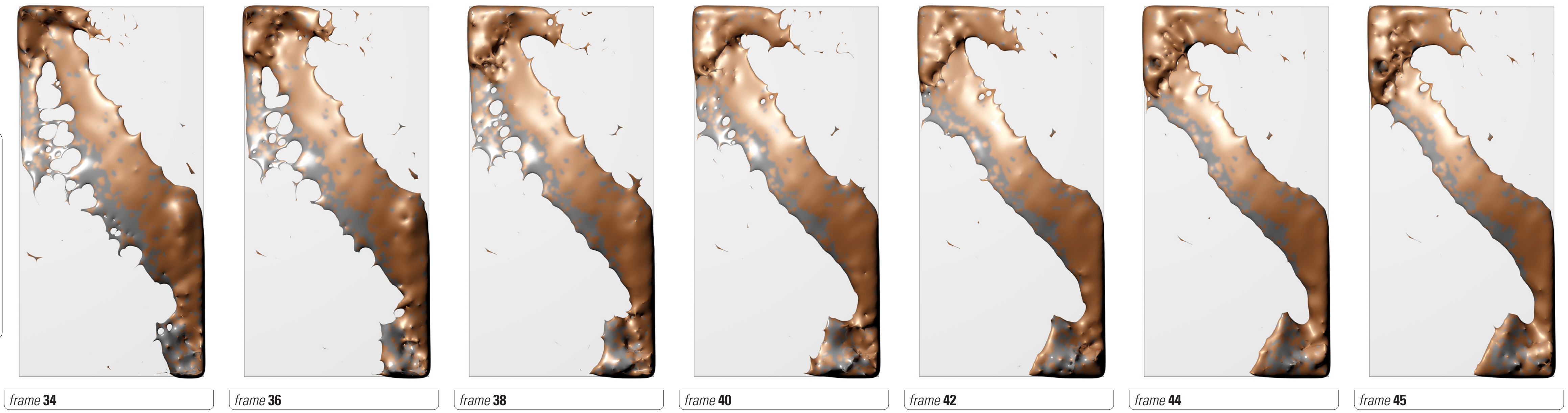


Frame 15 of the aluminium and copper blending simulation presented in 3.2.1.

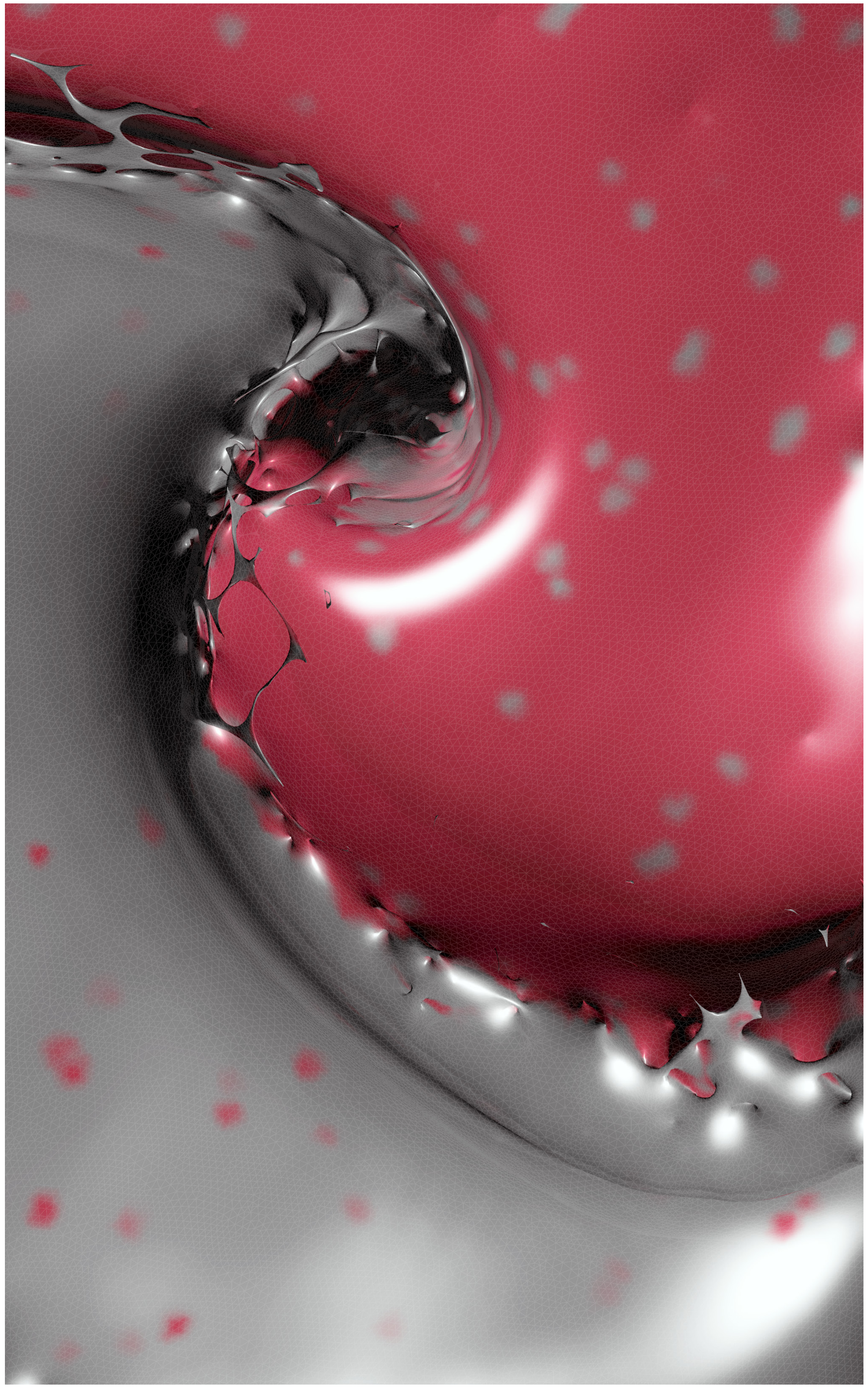




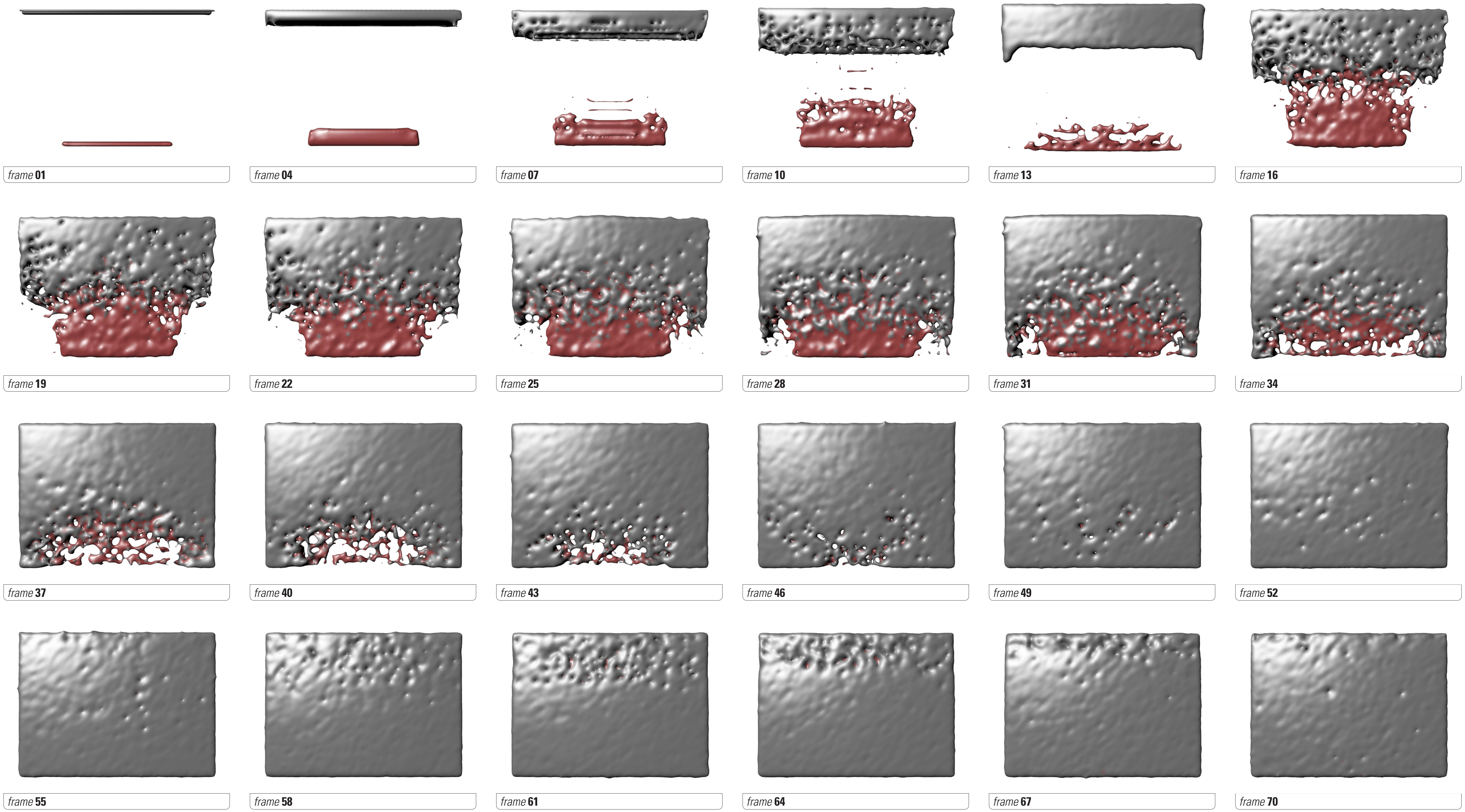
Particles
Type: Liquid
Resolution: 20.0
Density (copper): 7,898.0 kg/m^3
Viscosity (copper): 0.00312 Pa·s
Liquid Temperature (copper): 1,473K
Density (aluminium): 2,375.0 kg/m^3
Viscosity (aluminium): 0.001379 Pa·s
Liquid Temperature (aluminium): 933K
Ambient Temperature: 400K



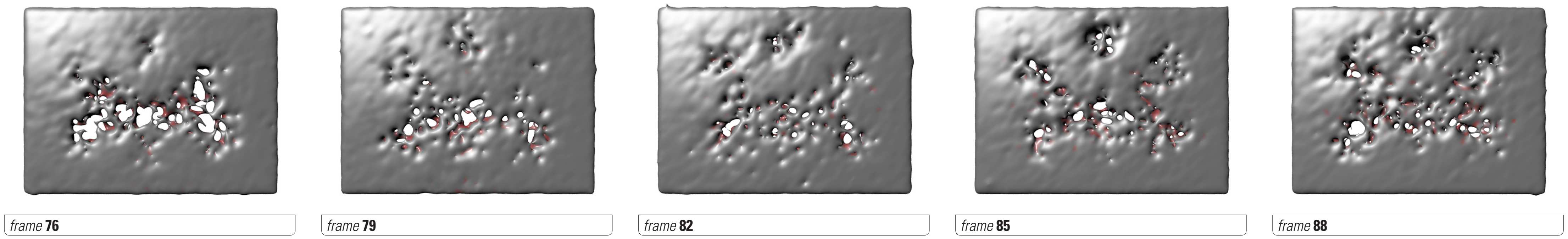
The full copper and aluminium mixing simulation, presented in 3.2.1.



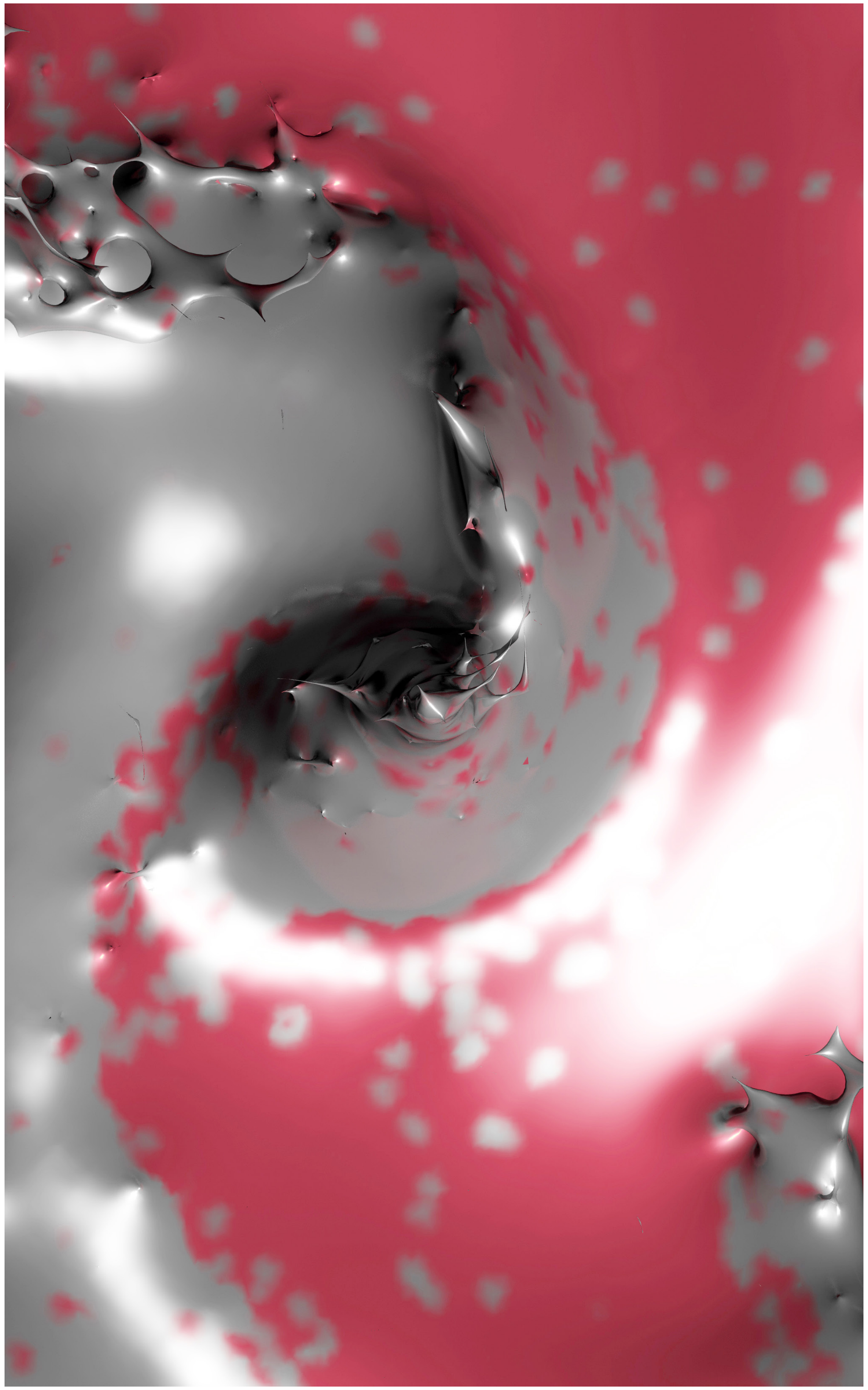
Zoom out view of the two-liquid fusion simulation in page 37.



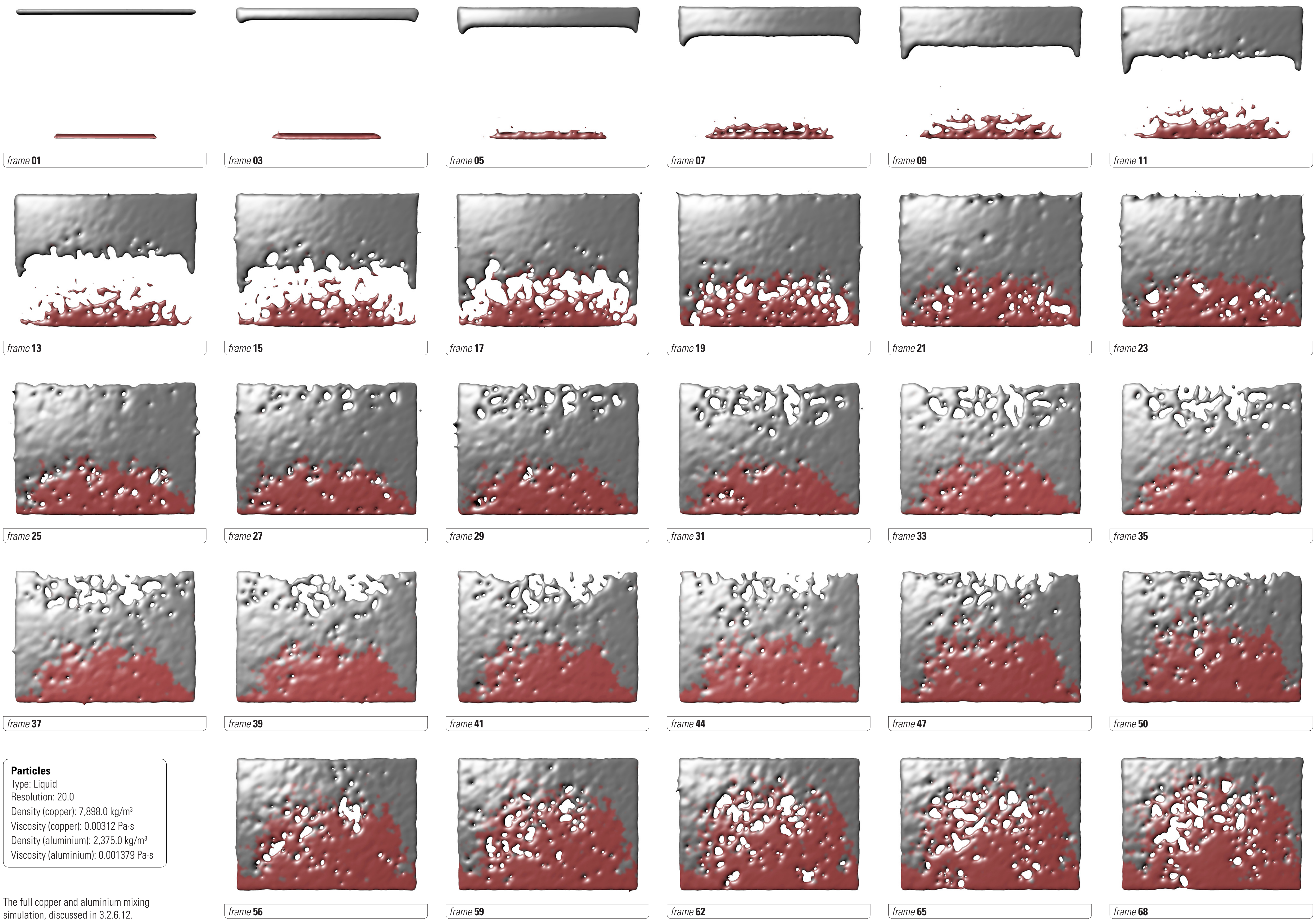
Particles
Type: Liquid
Resolution: 20.0
Density (copper): 7,898.0 kg/m^3
Viscosity (copper): 0.00312 Pa·s
Density (aluminium): 2,375.0 kg/m^3
Viscosity (aluminium): 0.001379 Pa·s



The full copper and aluminium mixing simulation, discussed in 3.2.6.6.

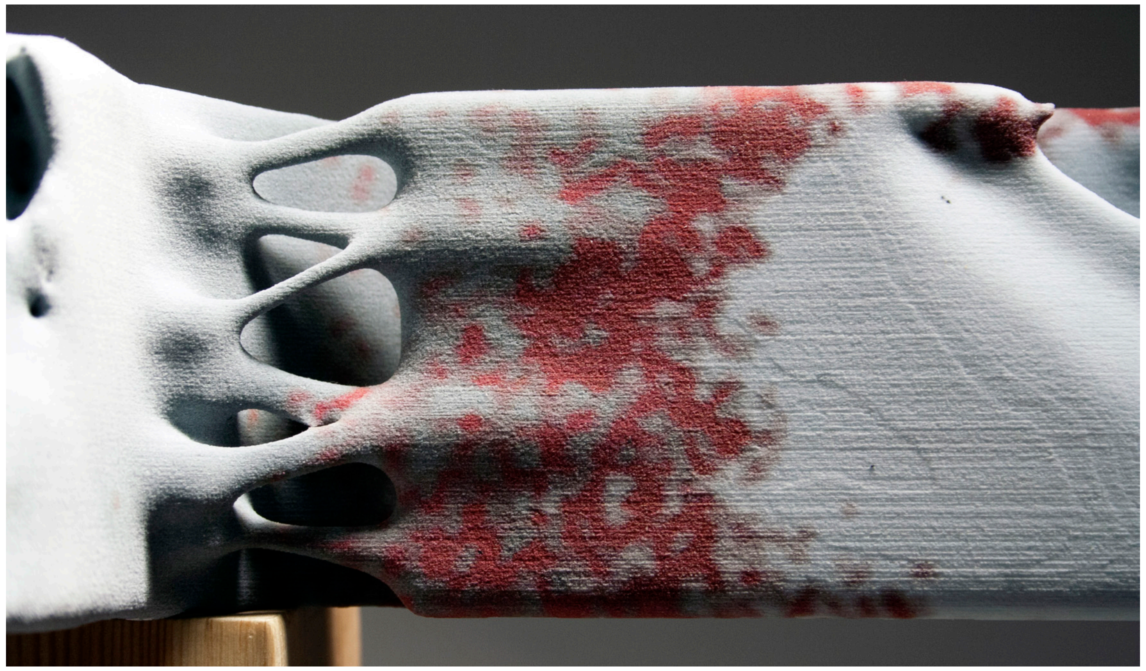


Close-up of a two-liquid fusion simulation.

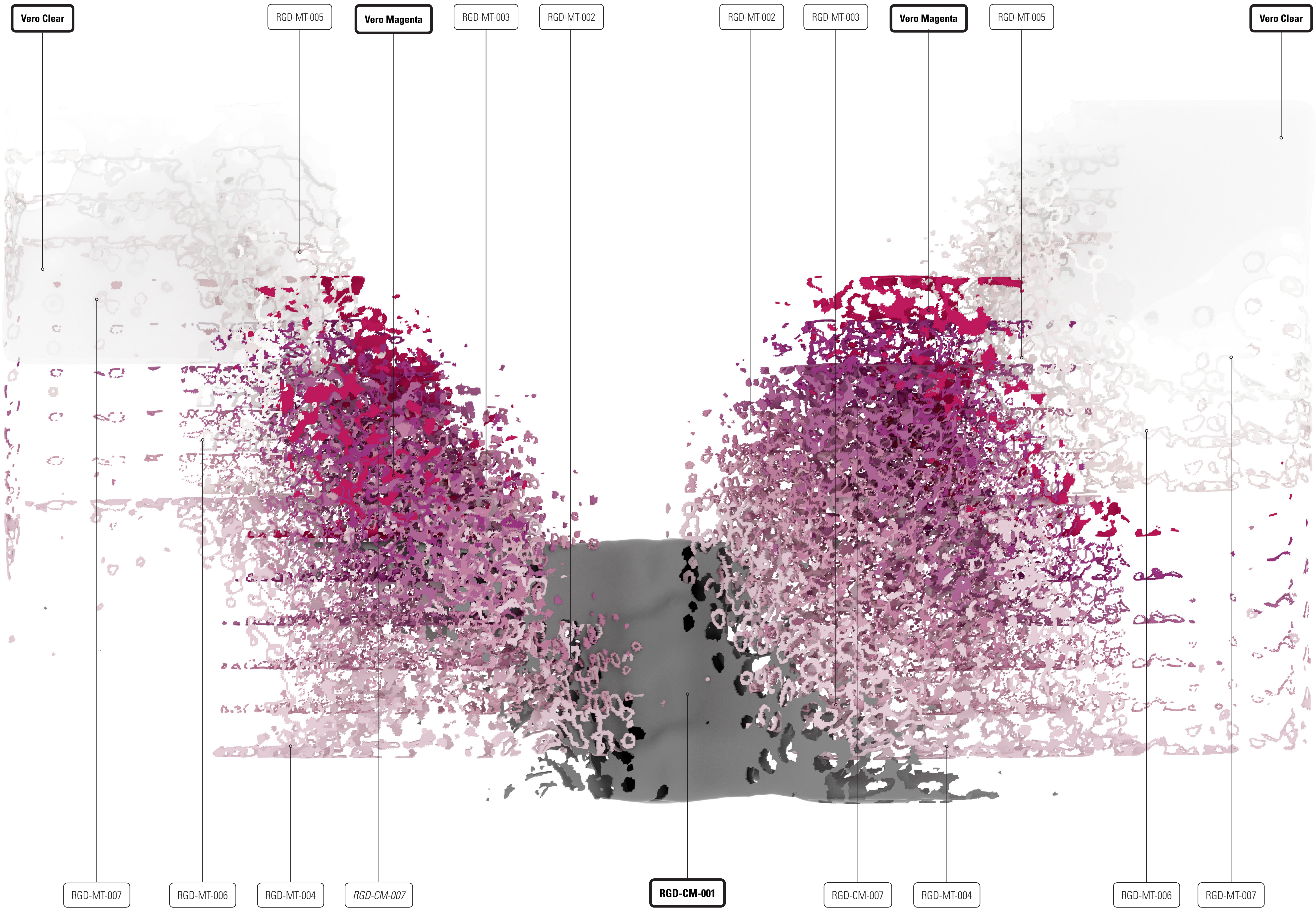


Particles
Type: Liquid
Resolution: 20.0
Density (copper): 7,898.0 kg/m^3
Viscosity (copper): 0.00312 Pa·s
Density (aluminium): 2,375.0 kg/m^3
Viscosity (aluminium): 0.001379 Pa·s

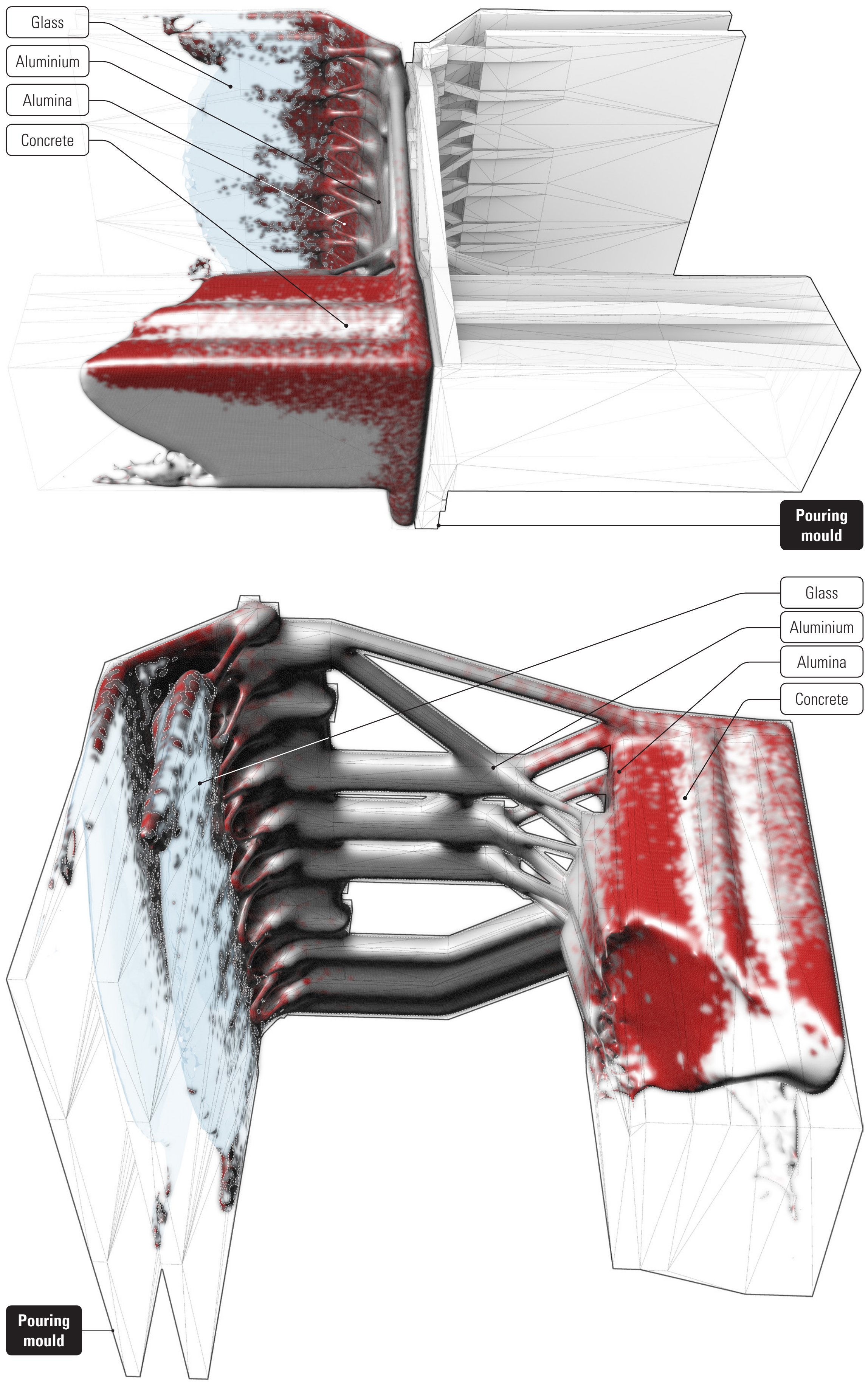
The full copper and aluminium mixing simulation, discussed in 3.2.6.12.



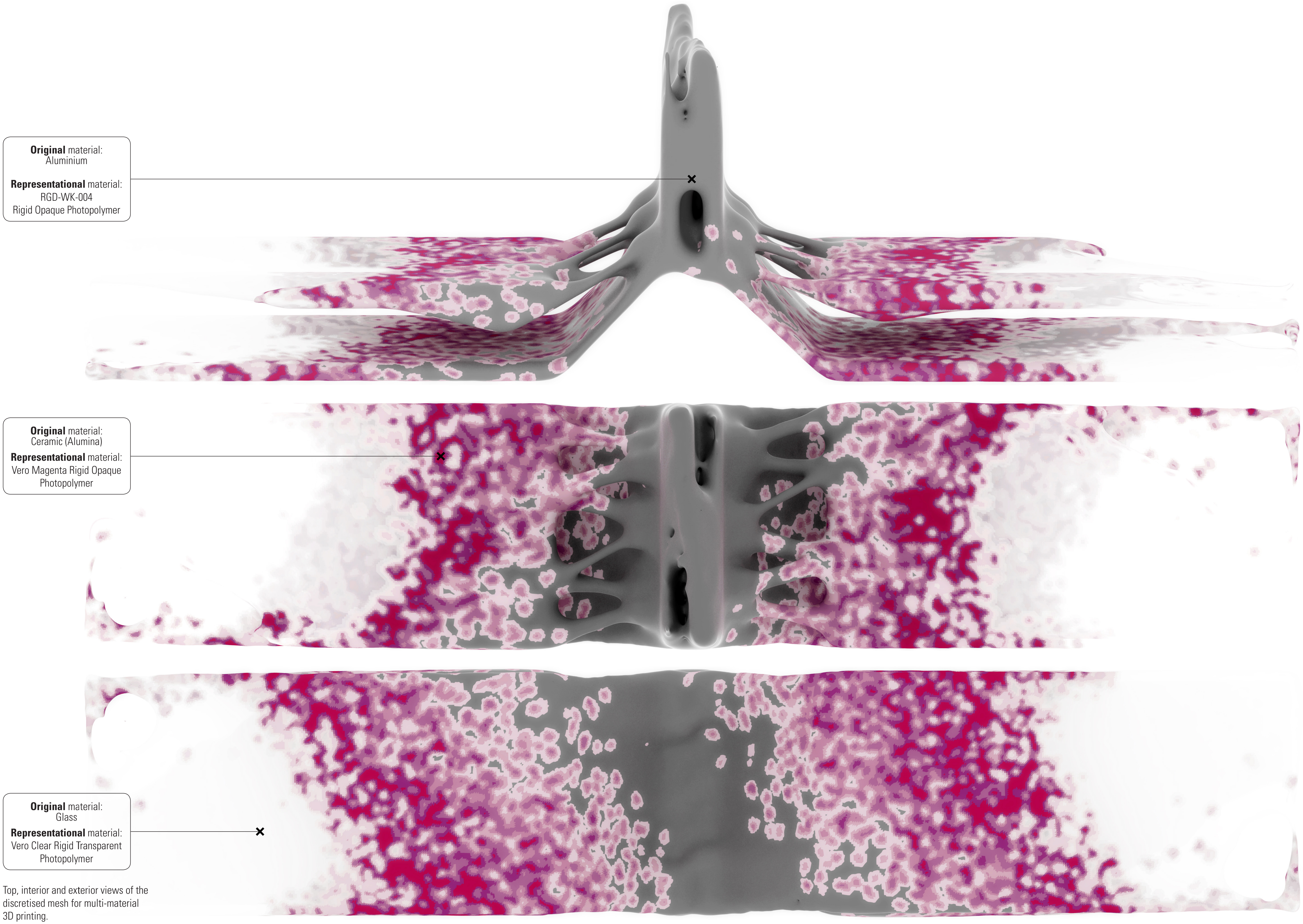
Views of the multi-colour 3D print (top image from the Royal Academy Summer Exhibition 2016).



External exploded view of the discretised multi-material mesh for 3D printing.



Design studies a curtain wall panel conneciton to its adjacent concrete floors slab with an FGM.



Top, interior and exterior views of the discretised mesh for multi-material 3D printing.

Email Correspondence with Iain Bleakley

From: Iain Bleakley [mailto:iain.bleakley@akt-uk.com]
Sent: 25 May 2016 12:13
To: Kostas Grigoriadis <Grigoriadis@aaschool.ac.uk>
Subject: RE: PhD Question

Hi Kostas,

Just back from Hols.

Images are of max deflection and max stress on a double glazed unit (this is for the worst case pane of glass which in this case is the outer pane). Maximum stress and maximum displacement occurring at the middle although there are some less high stress concentrations at corners and edges on other faces (the image shown is only for the highest stress). For the stresses in the framing members the highest stresses 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- Pierre Luigi Nervi and the concrete shell builders off the '30s knew this, just like the cathedral master builders doing complicated ribbed vaults did. This concept was big for concrete and exists when we think of profiles like the steel I beams. Glass is technically 'over sized' in some areas to allow for the maximum stresses in the overall pane. If thickness varied in the glass this could allow for more efficient use of the material. The downsides of doing this with glass is that it may cause for some pretty wacky visual distortions and of course finding a way to mass produce cost effectively.

I meant to say this in the last email- if you are using any of those images there might be a copyright thing about using those images- you might want to mention the software- the glass is done using 'SJ MEPLA', the bracket using 'SOFiSTiK' and the frame using 'SAP 2000'. And would be nice to be credited too.

Feel free to run any more thoughts by me and keep me in the loop with the final thing

Best

Iain

From: Kostas Grigoriadis [mailto:Grigoriadis@aaschool.ac.uk]
Sent: 16 May 2016 11:23
To: Iain Bleakley
Subject: RE: PhD Question

Hi Iain,

Thank you very much for sending these. They are great.

There was one last question that I had in regards to what the two images for the glass mean. Presumably in the first one, the maximum stress concentration would be in the centre of the panel and in the second one, the maximum displacement would be at the four corners. If so, would there be a way to in principle reduce the stress concentration in the centre, by adding more material perhaps or by adding reinforcing elements there?

Also, in regards to the stress distribution for the frame, the image shows that this would be maximum at the corners of each of the frames?

Regards,

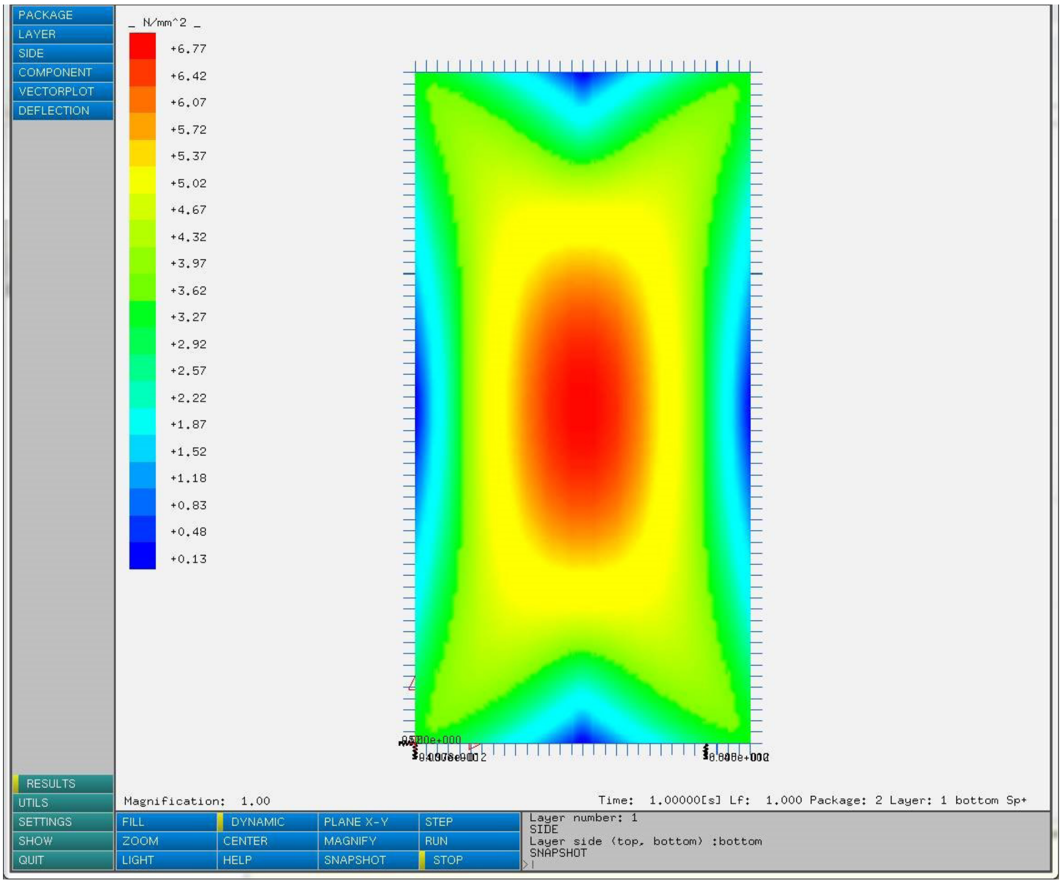
Kostas

From: Iain Bleakley [mailto:iain.bleakley@akt-uk.com]
Sent: 11 May 2016 16:59
To: Kostas Grigoriadis <Grigoriadis@aaschool.ac.uk>
Subject: RE: PhD Question

Kostas,

For the glass I can only take snapshots rather than hi-res jpegs. See below for stress and displacement plots. Elevational views of brackets are attached. Frames stress distribution (there isn't a colour contour option for the frames analysis) and deflected shape (magnified) also attached. Hope this helps- sorry for the response lag!

Iain



From: Kostas Grigoriadis [mailto:Grigoriadis@aaschool.ac.uk]
Sent: 04 May 2016 15:47
To: Iain Bleakley
Subject: RE: PhD Question

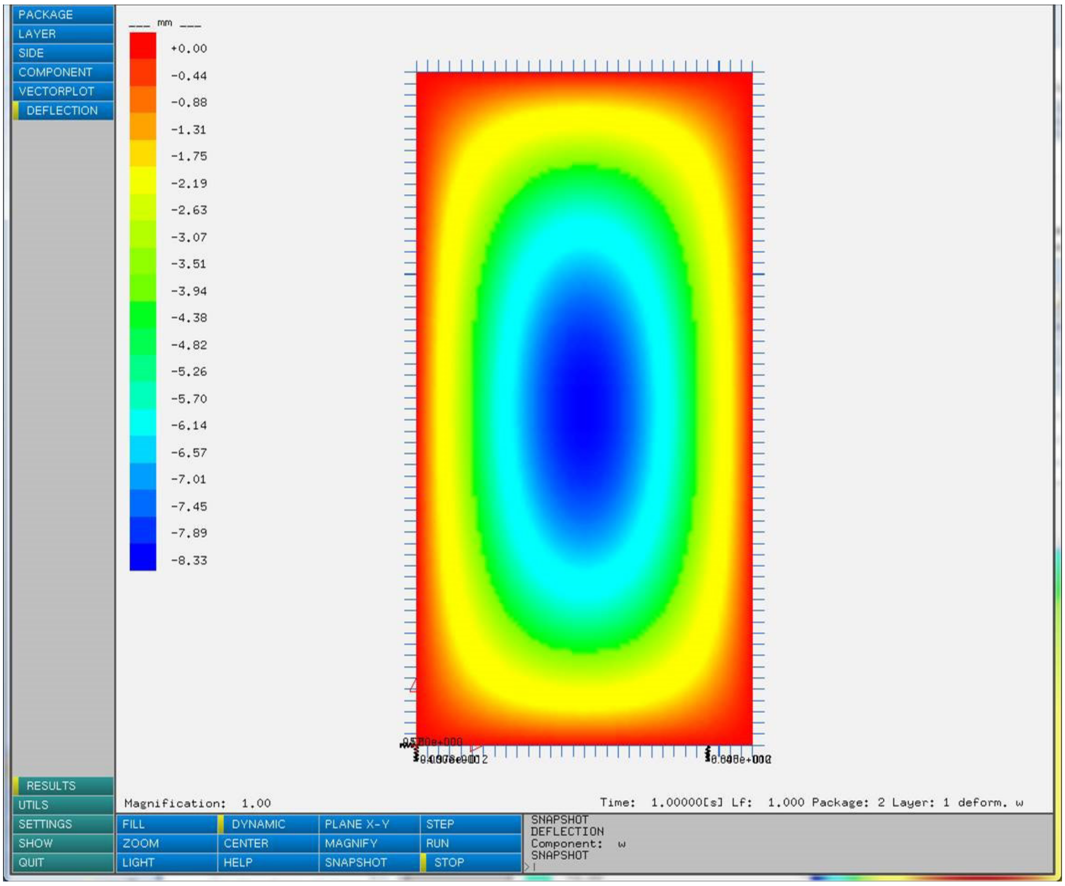
Hi Iain,

Thanks a lot for these. They are great. One last thing that would help a lot would be to have flat elevations of the analyses images, so that I can use these to map the colours on the polysurface in Rhino.

In terms of the output for the curtain wall, ideally there would be one stress analysis for the glass (like the first image in your email) and one for the aluminium framing, which I could then combine to give the overall picture. Would that be possible?

Many Thanks,

Kostas



From: Iain Bleakley [mailto:iain.bleakley@akt-uk.com]
Sent: 04 May 2016 15:36
To: Kostas Grigoriadis <Grigoriadis@aaschool.ac.uk>
Subject: RE: PhD Question

Hi Kostas,

This is the highest res. the software exports- hope that is O.K?

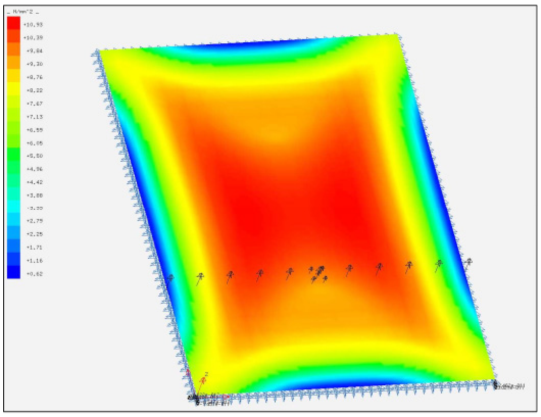
The loads we could expect on the curtain wall would be 1 kN/m2 of wind load plus the self weight of the glass and framing which can be assumed to be in the range of 1.5 to 2 kN/m length. In terms of output what were you looking for?

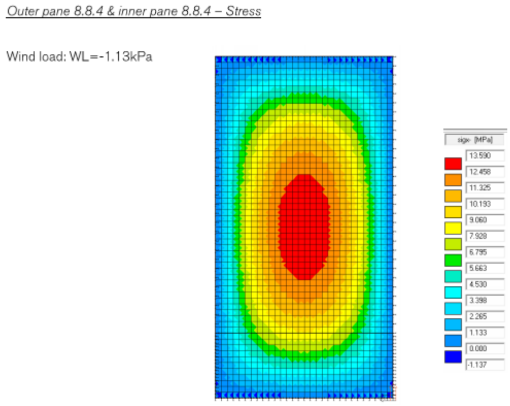
The glass will be put under stress and deflection depending how thick the build up is and transfer the loads to the framing members which also deflect depending mainly on the profile depth and spacing (in general for framing members stress is usually less of an issue but of course that would be different with different materials or perhaps key regions in a 'multi-material'). Tthe loads are then transferred through the brackets to the primary structure with the bracket stress determining how thick a bracket is and the size and no. of the fixings into the slab.

Are you interested in the framing or the glass. It is a separate analysis package to analyse glass compared to aluminium framing members or brackets. So there wouldn't really be a situation where you would have the whole curtain wall including the glass as one result image file. See below for examples of the sort of outputs you might get.

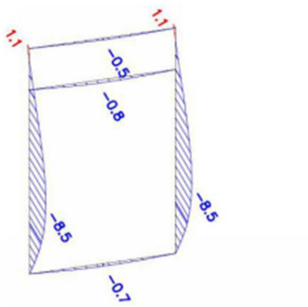
Iain

Example glass stress analysis output





Example frame analysis results



Best
Iain

From: Kostas Grigoriadis [mailto:Grigoriadis@aaschool.ac.uk]
Sent: 21 April 2016 15:55
To: Iain Bleakley
Subject: RE: PhD Question

Hi Iain,

Thanks a lot for this.

Initially, I was wondering if it would be possible to have the images in high resolution or even better the coloured mesh file would be great.

Secondly, maybe I didn't clarify this as much as I should have, but what I was really after were the loads on the actual curtain wall part as opposed to the bracket… If that would be too time-consuming to calculate, then perhaps some images of standard loads on a curtain wall might be fine too.

Best Regards,

Kostas

From: Iain Bleakley [mailto:iain.bleakley@akt-uk.com]
Sent: 21 April 2016 13:22
To: Kostas Grigoriadis <Grigoriadis@aaschool.ac.uk>
Subject: RE: PhD Question

Kostas,

Here are some screen shots of bracket finite element structural analysis showing the stress distribution. I have attached the Rhino file so you have some context- essentially there are 2 angle brackets that fix through the mullion into a steel spigot which sits inside the profile at the joint. The brackets are connected back to the slab.

I just made up some typical wind load assumptions and weight of typical glazed curtain walling based on a central London location.

The images are stress distribution for the weight of the curtain walling of the bracket ('weight') and the effect of the wind load on the bracket ('wind'). Hope this is useful.

Hope this helps, really sorry I took so long to get back to you!

Best of luck with your project- let me know how it goes.

Regards

Iain

From: Kostas Grigoriadis [mailto:Grigoriadis@aaschool.ac.uk]
Sent: 12 April 2016 10:21
To: Iain Bleakley
Subject: RE: PhD Question

Hi Iain,

Thanks for getting back and no problem, next week sounds good.

Look forward to it.

Regards,

Kostas

Sent from my Windows Phone

From: Iain Bleakley
Sent:12/04/2016 09:51
To: Kostas Grigoriadis
Subject: RE: PhD Question

Hi Kostas,

I'll get that done for you by next week. Sorry things have been busy and I was ill the week when I aimed to have it done for you so been catching up from that. Hope that's still O.K

I have some previous stuff but that is from the bracket of a unitised type of facade system. Not sure if that is helpful, it's obviously not project specific for your work.

Sorry for making you chase me! Hope next week would be O.K. I'll try my best this week but don't want to overpromise.

Iain

From: Kostas Grigoriadis [mailto:Grigoriadis@aaschool.ac.uk]
Sent: 09 April 2016 13:42
To: Iain Bleakley
Subject: RE: PhD Question

Hi Iain,

I hope all is well and things are not too busy at the office.

I was wondering if you have been able to have a look at the load analysis by any chance?

Thanks,

Kostas

From: Iain Bleakley [mailto:iain.bleakley@akt-uk.com]
Sent: 02 March 2016 14:03
To: Kostas Grigoriadis <Grigoriadis@aaschool.ac.uk>
Subject: RE: PhD Question

Sorry Kostas been really busy- going to have a look at this the week after next.

Iain

From: Kostas Grigoriadis [mailto:Grigoriadis@aaschool.ac.uk]
Sent: 10 February 2016 22:59
To: Iain Bleakley
Subject: RE: PhD Question

Hi Iain,

Thanks again for taking the time to meet today and also for helping out.

As discussed, I am attaching the Rhino file containing the detail that I had sent previously and also the extension of it (measuring 3000 x 1500 mm).

In terms of your points below, although the detail is rather 'context-less' so to speak, these might help:

- A typical location in Central London, mid/high-rise (15-20 stories), office building, external and internal access.

- I am not sure about this, but a standard behaviour (if this even exists) would be fine.

- The building would be rectilinear.

- Regarding the last 3 points, I am not entirely sure either, but again it could be a matter of using parameters that apply for standard office block buildings.

I hope these are ok and please do let me know if you might need anything else.

Regards,

Kostas

From: Iain Bleakley [mailto:iain.bleakley@akt-uk.com]
Sent: 10 February 2016 11:26
To: Kostas Grigoriadis <Grigoriadis@aaschool.ac.uk>
Subject: RE: PhD Question

Hi Kostas,

Finite element models of brackets are typically done by a contractor. Unless the loads or distance the bracket has to span are unusual- on a typical glazed system, a facade designer would not be especially concerned with this. We do use this software for more complicated problems to prove the feasibility. I can be a I can talk you through what I think are the important considerations for a facade designer. See below bullet points for a starting point. Bring along the scheme for your project or any info you have and we can discuss further. Here are a few bullet points for you to have a think about- what I would consider key issues you might want to think about:

- Considering the type of loads the facade might see. This will be based on the location, height, the use, access and maintenance strategy and so on.

- Further to this- how the facade behaves when the slabs deflect and frame sways is also important to understand. Movement is a key issue we deal with and affects the architecture in terms of panels proportions, joint sizes and system choice.

- The type of building (complex geometry or rectilinear, skyscraper or low rise etc) plays a part in determining the most appropriate facade system. Stick or unitised etc.

- The loads will affect the depth of the framing members which affect sight lines. Likewise large spans will also have this effect.

- Construction methodology is important to consider as it has cost, quality and safety implications. Likewise fabrication of the panels themselves should be considered. Understanding how a facade is fabricated and assembled is important as then you can be aware of the possibilities.

- Materials considerations is of course a key part of facade considerations. Meaning the use of a combination of opaque areas, high performance glazing and perhaps shading elements

Hope that helps.

Come round to our offices at 530.

Cheers

Iain

From: Kostas Grigoriadis [mailto:Grigoriadis@aaschool.ac.uk]
Sent: 09 February 2016 17:56
To: Iain Bleakley
Subject: RE: PhD Question

Hi Ian,

I hope all is well and you had a good weekend.

As discussed previously and prior to our meeting tomorrow, please find attached a couple of images that show what I had in mind on doing the structural analysis on. Basically, the part is a typical curtain wall glazing and all I was after was to work out the loads on this segment. In terms of the specific output, some images like the attached jpeg examples would be ideal.

It'd be great if you could let me know whether this might be doable and if not we can perhaps discuss another way that it can be done.

Many Thanks,

Kostas

From: Iain Bleakley [mailto:iain.bleakley@akt-uk.com]
Sent: 28 January 2016 09:33
To: Kostas Grigoriadis <Grigoriadis@aaschool.ac.uk>
Subject: RE: PhD Question

Kostas,

Sounds like a plan. Happy to help.

Best

Iain

Kind Regards,

Iain Bleakley

Senior Facade Engineer

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M +44 (0)7870 892 557

iain.bleakley@akt-uk.com

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From: Kostas Grigoriadis [mailto:Grigoriadis@aaschool.ac.uk]
Sent: 27 January 2016 19:23
To: Iain Bleakley
Subject: RE: PhD Question

Hi Ian,

Great, thanks, we can arrange a specific time a bit closer to the date perhaps.

I will also send some more information when I find some time, so that you can have an idea of what I am after beforehand.

Thanks again,

Kostas

Sent from my Windows Phone

From: Iain Bleakley
Sent: 27/01/2016 19:15
To: Kostas Grigoriadis
Cc: Adiam Sertzu
Subject: Re: PhD Question

Kostas,

10th would suit me.

Cheers

Iain

Sent from my iPhone

On 27 Jan 2016, at 19:14, Kostas Grigoriadis <Grigoriadis@aaschool.ac.uk> wrote:

Hi Ian,

Thank you very much for helping out with this.

Next Monday will be quite difficult to meet up and after that I'm off for a week or so.

Would Wednesday the 10th of February work by any chance?

Regards,

Kostas

Material Simulation Studies not Included in the Main Thesis Text

Simulation Agency

According to Watanabe and Sato (2011) graded compositions are either of continuous or step-wise structure with techniques such as powder metallurgy resulting in the former, and casting generating continuous gradations. In terms of the latter, the method consists of particles of one material contained within a preheated spinning mould, into which a second molten metal is poured. The centrifugal forces acting on the mould during processing, as well as the different densities and viscosities among other parameters, force the two substances to be positioned at the two opposite ends of the mould with a gradient composition forming between them.

Resemblance of Digitally Simulated to Manufactured Multi-Materials

In order to initially test out this physical principle in a digital environment, a simulation was set out using in this instance aluminium (Al) and Titanium tri-aluminide (Al_3Ti). The density, viscosity and other parameters attributed accordingly, a vortex daemon was placed at the world origin point in the scene (Figure 01) and the materials were released into a cylindrical mould with a time lag between the first and second pouring. Remarkably, and similarly to physical centrifugal casting, having gone into a formation that was changing periodically over regular intervals, the two substances eventually found their way towards either end of the container (Figure 105) while at the same time being fused in the middle in a gradient manner.

Problem 01- Gradient Extent of Digitally Fused Materials

In this instance and although the formation of an FGM was achieved digitally, a main remark and problem posed is the *extent of the gradient* at the area that the two materials were fused. As previously described, in order for the particle based output of the simulation to be visually discernible and in some cases 'render-able', a polygon mesh has to be generated that is essentially a three-dimensional skin over the outmost particles of the blended system. In order for gradients to be mapped on this mesh, "per-vertex data is generated [and…] stored as a colour set [that…] can be visualized by making it the current colour set of the mesh" (Autodesk Maya 2015 | Help, 2015), with the overall visualization of the total data effectively giving the impression of a gradient (Figure 02).

The ways this gradient is calculated by default, however, is through a built-in algorithm within the program that operates independently to any physical reality. Physically, the densities and other compositional characteristics of the individual materials to be fused affect the gradient extent in terms of length and area covered, as well as in terms of the potential micro-dispersal of one substance into another. In this regard, further research and customization of the tool and software is required for the gradients to be attributed accurately and subject to physical material parameters.

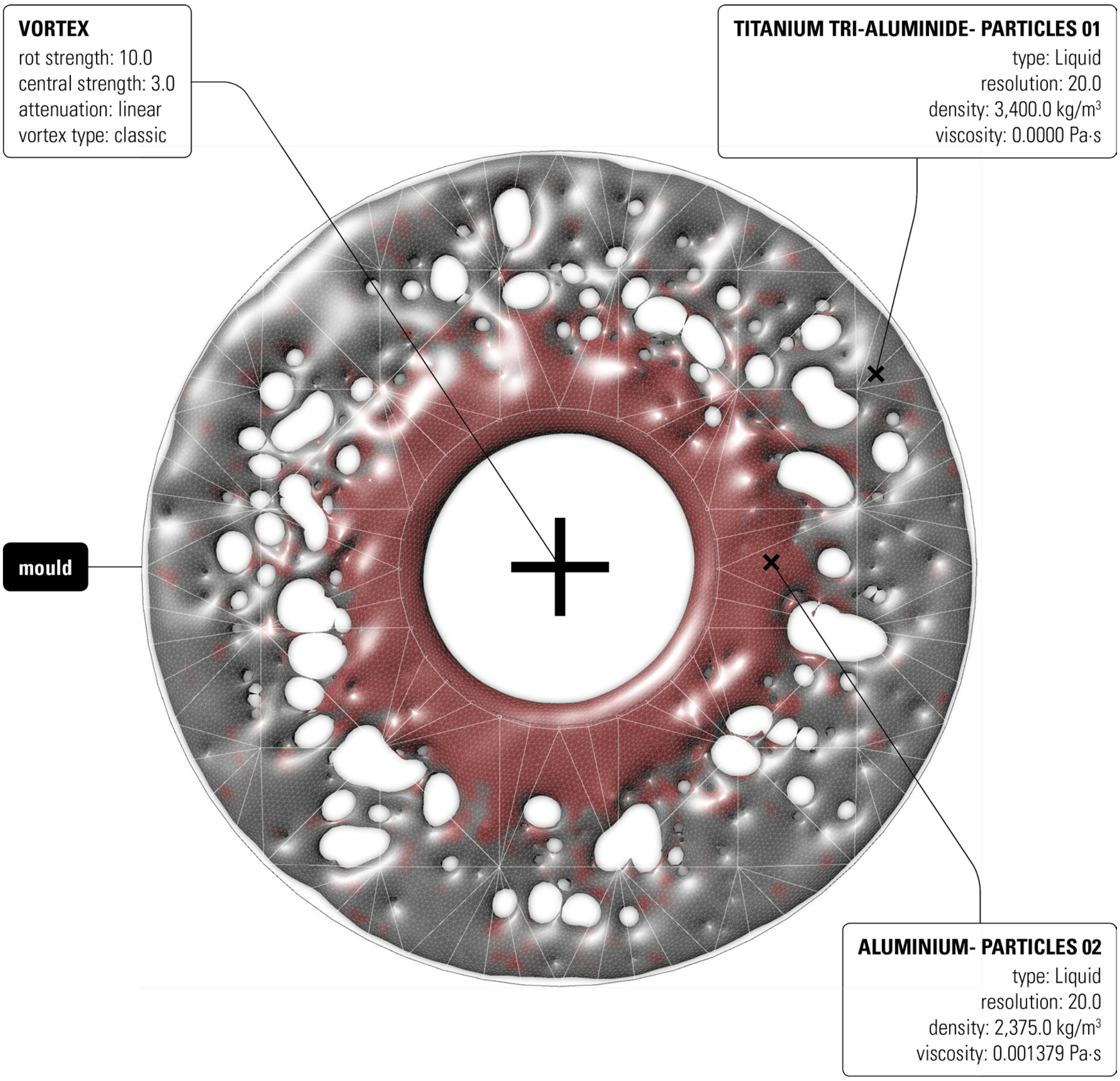


Figure 01: The Centrifugal Force Simulation at frame 26, showing the positioning of the vortex daemon, as well as the properties of the blended materials.

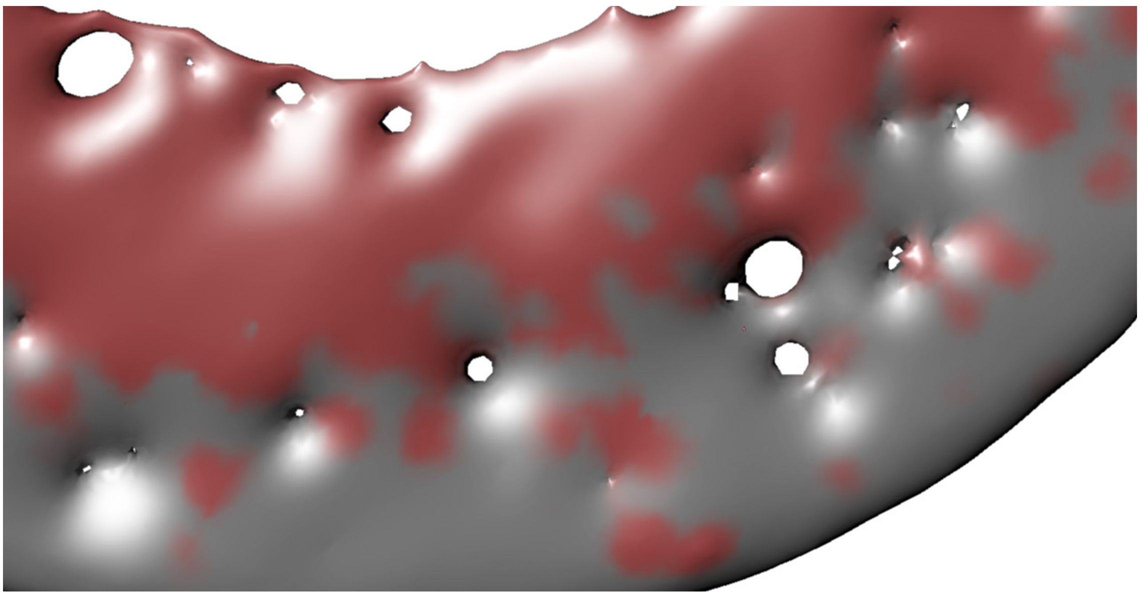


Figure 02: Detail of the Region between the Fused Materials.

In addition, according to research by El-Hadad et al. (2010), it was found that “the centrifugal casting processing temperature in some reported studies showed a remarkable effect on the Al_3Ti particles distribution in the fabricated Al-Al_3Ti FGM [...] The processing temperature [...] showed a strong influence not only on the Al_3Ti particles shape but also on the distribution of Al_3Ti particles size and volume fraction”. This effectively means that when examining the material output from the casting process at scales of 0.05mm and above, one should be able to discern firstly the particles of the dispersed material (Al_3Ti in this case) forming platelets and secondly that the shape of these should vary according to temperature fluctuations as well as the centrifugal force intensity. Watanabe and Sato (2011) state that “it has also been found that the particle size gradient in the FGM becomes steeper with increasing the G number or with decreasing the mean volume fraction of particles”.

Although there would be a microscope needed in order to discern these formations of the physical material, in the digital environment there is the ability of large magnitudes of zooming into specific parts to examine whether this clustering is the case as well. Having examined the polygon mesh that was generated in the simulation, no visible platelets were formed, which only illustrates *the limited micro level material structuring capabilities of particle system elements* (Figure 03).

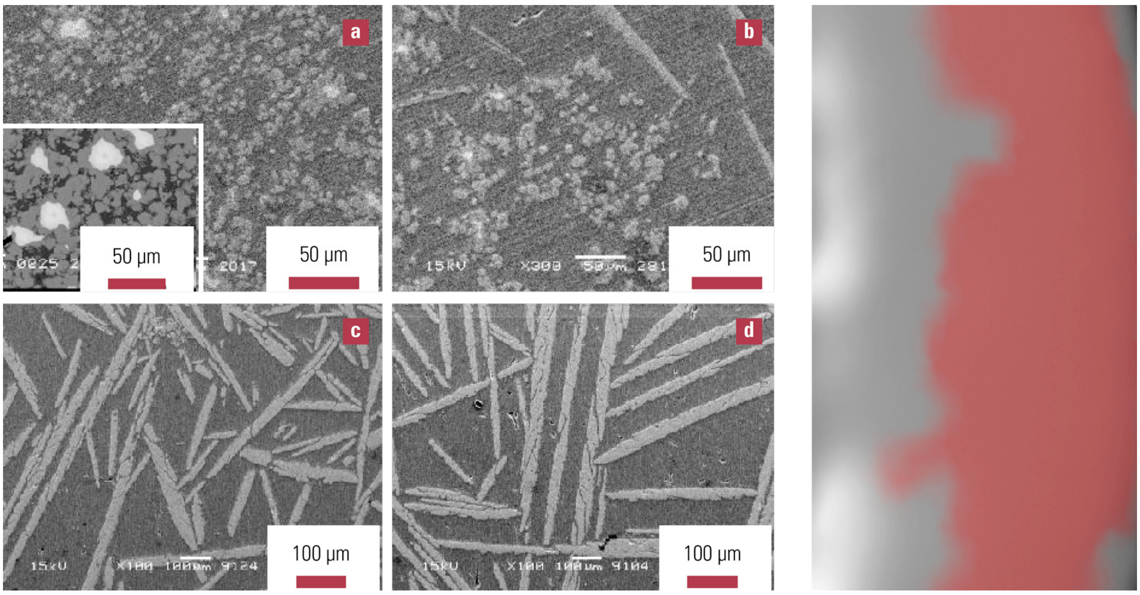


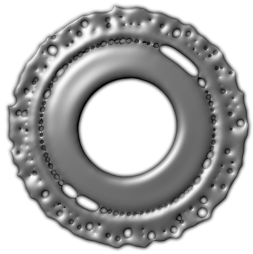
Figure 03: FGM Sample Details. On the left are “Scanning Electron Microcopy (SEM) micrographs of RCMPM [Reaction Centrifugal-Mixed Powder Method]- [Aluminium-Titanium Trialuminide] FGMs processed at different temperatures” (El-Hadad et al., 2010, p. 4650) (a. at 1,150ºC, b. at 1,250ºC, c. at 1,350ºC, and d. at 1,450ºC). On the right is the gradient formed between the same (virtual) Aluminium-Titanium Trialuminide materials simulated at 1,350ºC.

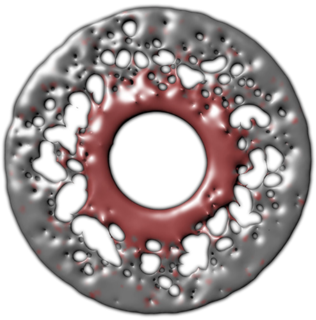
Alternative Simulation Models

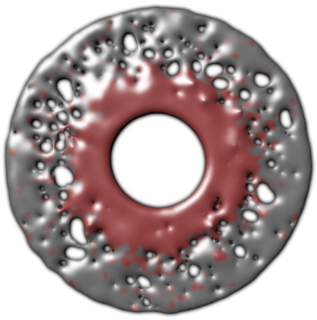
Similarly to the aforementioned gradient extent issue, customization of the software would be required here, with material formation patterns from existing scientific research informing the

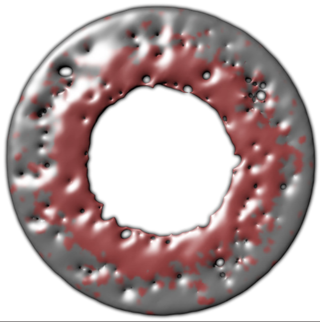

frame 004


frame 007


frame 010


frame 025


frame 027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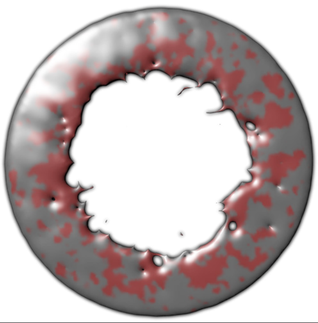
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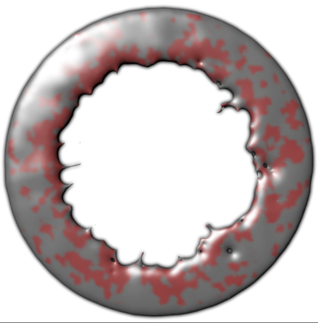
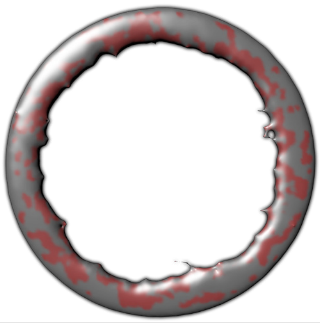

frame 050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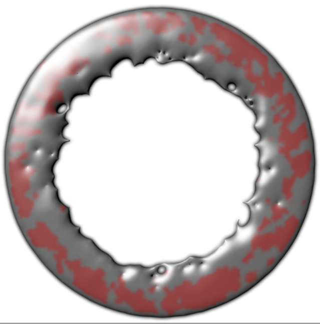
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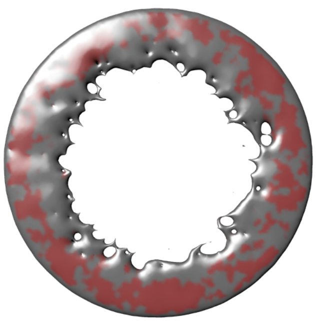
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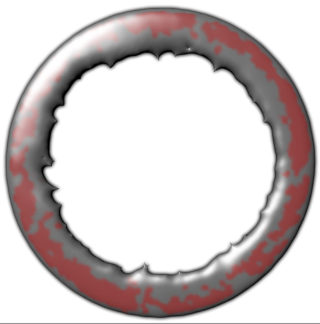
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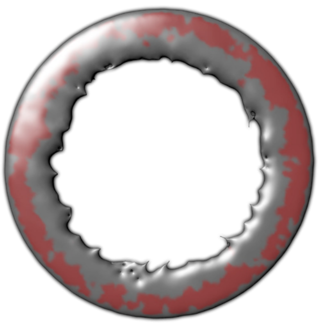
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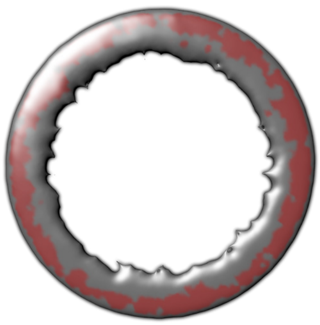
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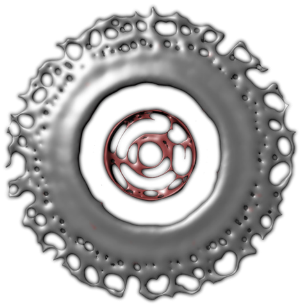
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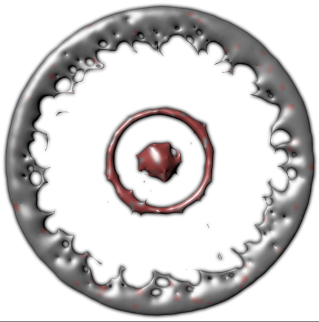
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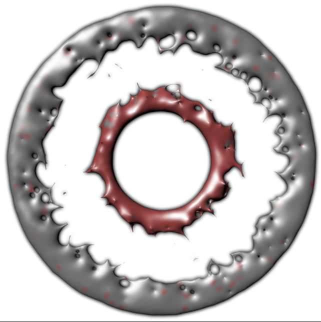
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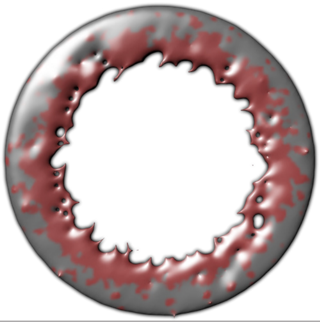
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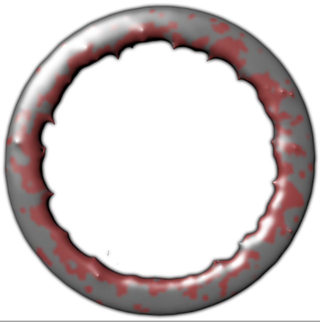
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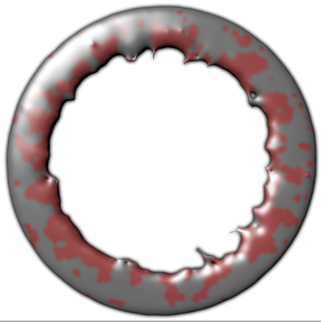
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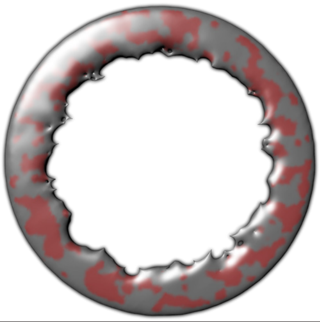
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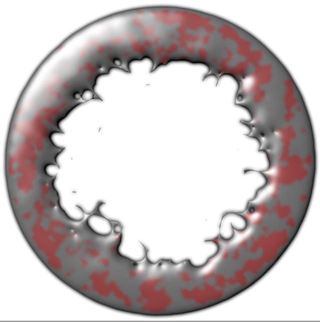
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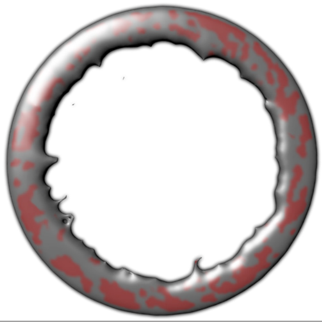
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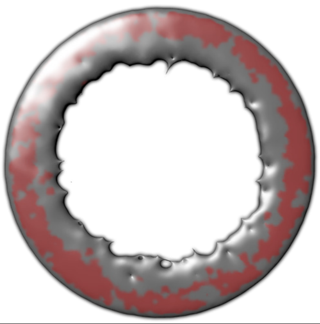
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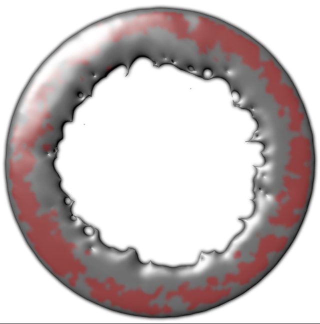
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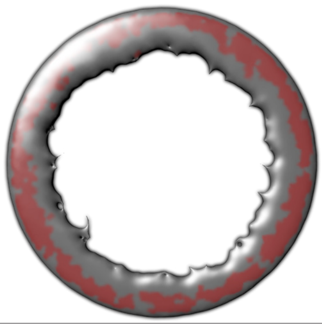
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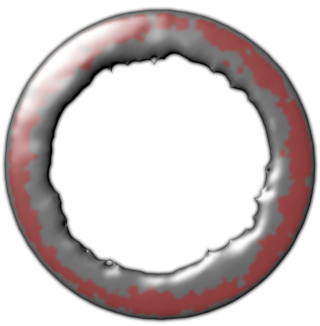
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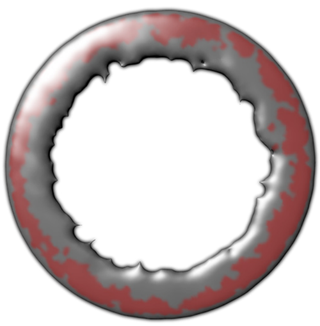
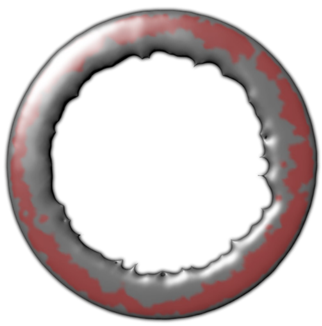

frame **107**


frame **110**

programming of the behaviour of the particles. This would be in order to achieve results that are closer to physical material reality. Alternatively, according to Winsberg (2015), a type of simulation that is a hybrid of particle and field based methods is called a multi-scale simulation.

> "A good example of this would be a model that simulates the dynamics of bulk matter by treating the material as a field undergoing stress and strain at a relatively coarse level of description, but zooms into particular regions of the material where important small scale effects are taking place, and models those smaller regions with relatively more fine-grained methods. Such methods might rely on molecular dynamics, or quantum mechanics, or both—each of which is a more fine-grained description of matter than is offered by treating the material as a field."

Winsberg (2015), goes on to analyse the subcategories of multi-scale simulations that are namely parallel and serial modelling, each with their own pros and cons in regards to the information that can be derived from them. Without delving into further details about these, the point in effect here is that there can be further scope in investigating alternative simulation models, should a structural evaluation of the multi-material segment indicate that micro-scale formation in graded materials has an impact on material and effectively structural behaviour and adequacy.

The Shortfall of Structural Criteria

This brings forth another main weakness in what has been presented, which namely concerns the lack of any structural evaluation that could occur in parallel to the workflow and that would enable a comprehensive understanding of the multi-material formation at any time of the process. This lack has been the case because, as mentioned briefly, and as although there have been attempts to consult with engineers and materials scientists[01], performing structural analyses on complex graded material entities is a highly-specialised and notoriously difficult process. In this sense, there can be another area of research and investigation, in which these types of criteria are established by identifying and consulting with researchers that specialise in graded material analyses.

---

01 Namely, at Imperial College in London.

RGB Data to TXT File RealFlow Graded Mesh Data Exporting (Python Script, by Alex Ribao from Next Limit Technologies)

```
from colorsys import *

# interpolate using RGB
def interpolateColorsRGB( rgbs, rates ):
        tmpR = [ 0.0, 0.0, 0.0 ]
 for i in range( len(rgbs) ):
    c = rgbs[ i ]
    rate = rates[ i ]
    for i in range( 3 ):
      tmpR[ i ] += c[ i ] * rate

        return tmpR

# Write legacy mesh vertex weights to text file
def writeVertexWeights( mesh, filename ):
  f = open( filename, 'w' )
  vertices = mesh.getGeometry()[ 0 ]

  for i in range(len( vertices )):
    weights = mesh.getFluidsWeightAtVertex( i )
    colors = []
    rates = []

    for pair in weights:
      # Get color of the emitter
      emitter = scene.get_PB_Emitter( pair[0] )
      c = emitter.getParameter( "Color" )
      c = ( c.getX() / 255.0, c.getY() / 255.0, c.getZ() / 255.0 )
      colors.append( c )
      rates.append( pair[ 1 ] )

    # interpolate the colors
    result = interpolateColorsRGB( colors, rates )

    # write to file
    string = "%d %f %f %f\n" % ( i, result[ 0 ], result[ 1 ], result[ 2 ] )
    f.write( string )
```

```
   f.close()

#example
mesh = ParticleMeshLegacy01
filename = "/Users/Kostas/Desktop/vertexcolor.txt"

writeVertexWeights( mesh, filename )
```

Colour Rhino Mesh Vertices from TXT file (RhinoScript)

```
Option Explicit
 '-------------------------------------------------------------
 ' Subroutine: ImportPoints
 ' Purpose:    Import points from a text file.
 '-------------------------------------------------------------
Call ImportPoints
Sub ImportPoints

        Dim strMesh, arrVertexColours, arrColours(), i, arrVertices

        strMesh = Rhino.GetObject("Select Realflow Mesh", 32)

        arrVertices = Rhino.MeshVertices(strMesh)

        ReDim arrColours(Rhino.MeshVertexCount(strMesh)-1)

        ' Prompt the user for a file to import
        Dim strFilter, strFileName
        strFilter = "Text File (*.txt)|*.txt|All Files (*.*)|*.*|"
        strFileName = Rhino.OpenFileName("Open Point File", strFilter)
        If IsNull(strFileName) Then Exit Sub

        ' The the file system object
        Dim objFSO, objFile
        Set objFSO = CreateObject("Scripting.FileSystemObject")
        ' Try opening the text file
        On Error Resume Next
        Set objFile = objFSO.OpenTextFile(strFileName, 1)
        If Err Then
                MsgBox Err.Description
                Exit Sub
```

```
        End If

        Rhino.EnableRedraw False

        'Read each line from the file

        Dim strLine, counter, arrNumbers
        Dim intTest, a, strNewLine, test

        counter = 0

        Do While objFile.AtEndOfStream <> True
                strLine = objFile.ReadLine

                If Not IsNull(strLine) Then
                        ' Remove any double-quote characters
                        strLine = Replace(strLine, Chr(34), , 1)
                        arrNumbers = Rhino.Str2Pt(strLine)

                End If

                arrColours(counter) = RGB(arrNumbers(0) * 255, arrNumbers(1) * 255,
                arrNumbers(2) * 255)
                counter = counter + 1
        Loop

        arrVertexColours = Rhino.MeshVertexColors(strMesh, arrColours)

        Rhino.EnableRedraw True

        objFile.Close
        Set objFile = Nothing
        Set objFSO = Nothing

        Rhino.Print "Script End"

End Sub
```

Discretise Mesh According to Mesh Face Colour Similarity (RhinoScript)

```
Option Explicit
'Script written by <Kostas Grigoriadis>
'Script copyrighted by <Kostas Grigoriadis>
'Script version 08 July 2015 12:34:36

Call Main()
Sub Main()

	Const rhObjectMesh = 32

	Dim strObject, intIndex, arrColours, arrFaceVertices, arrFaces
	Dim arrFace, arrDeletion()
	Dim counter01, counter02
	Dim int00, int01, int02, int03

	strObject = Rhino.GetObject("Select mesh", rhObjectMesh)
	intIndex = Rhino.GetMeshVertices(strObject)(0)

	arrColours = Rhino.MeshVertexColors(strObject)
	arrFaceVertices = Rhino.MeshFaceVertices(strObject)
	arrFaces = Rhino.MeshFaces(strObject)

	counter01 = 0
	counter02 = 0

	For Each arrFace In arrFaceVertices

		int00 = arrColours(arrFace(0))
		int01 = arrColours(arrFace(1))
		int02 = arrColours(arrFace(2))
		int03 = arrColours(arrFace(3))

		If Not int00 + int01 + int02 + int03 = arrColours(intIndex) * 4 Then

			ReDim Preserve arrDeletion(counter02)
			arrDeletion(counter02) = counter01

			counter02 = counter02 + 1
```

```
                End If

                counter01 = counter01 + 1

        Next

        Call Rhino.DeleteMeshFace(strObject, arrDeletion)

End Sub
```

ANNOTATED BIBLIOGRAPHY

[1] Achten, H. H., 2003. New design methods for computer aided architectural design methodology teaching. *International Journal of Architectural Computing*, 1(1), pp. 72-91.

Analysed in the article are the design methods followed by three architects, namely Eisenman, van Berkel and Lynn. These are presented in order to allow students (of the author of the article) to gain an insight into the ways the computer is used in the design process and also to provide a framework for them to analyse and evaluate their own approach to design. The article is useful to the research for two main reasons, one being the very clear and rigorous structure that is followed of a. providing a brief mention of writings on design methodology since the sixties b. explanation of the benefits of conducting this research c. scope, limitations and elements (CAAD, ontology, method) of the analytical framework d. design method analysis and e. discussion of results. The second reason is the background provided about the history, shortfalls and relevance of the analysis of CAD methodologies in architecture, which could be used as an introduction to the multi-material design workflow proposed in the thesis.

[2] Allen, S., 1999. *Points + lines: diagrams and projects for the city*. New York: Princeton Architectural Press.

The book consists of Allen's theory and architectural projects relating to the concept of infrastructural urbanism. He starts off with a critique of postmodernism and analysis of the contemporary city, suggesting that an architecture of fields is an appropriate urban model in response. The characteristics of this consist of five propositions, namely having to do with intensive programming, distraction, site specificity, field conditions and post-collaging. Of particular relevance to the thesis are the parts of the book where architecture as a material practice and the architect operating through mediated practices are discussed, as well as most importantly the mentioning of postminimalist artists that deal with materials. More specifically, Le Va, Saret and Benglis' method of creating art that does not exert direct formal control on materials, but rather "establish the conditions within which the material will be deployed", is something directly related to the design methodology aspect of the research.

[3] Althusser, L., 1970. Ideology and ideological state apparatuses (notes towards an investigation). *La Pensée*, June 1970, 151, pp.67-125.

The essay, considered to be seminal in moving forward Marxist writings on the State, discusses the ways that state ideology is embedded into quotidian practices, therefore making its repressive potential impossible to escape. Thesis II that is put forward of ideology having a material existence, describes how actions become part of material practices and rituals, which are in their turn defined by what Althusser terms the ideological state apparatus, itself different from the repressive state apparatus. The essay was mentioned in the introductory text of New Materialisms: Ontology, Agency, and Politics as an example of the idea of aleatory materialism, or "materialism of the encounter" and it is relevant to the research in the part where the different types and takes on the concept of materialism are discussed.

[4] Anderson, J., 2009. *The green guide to specification: an environmental profiling system for building materials and components*. Oxford: Blackwell.

This publication consists of analyses of the environmental impact and lifecycles of over 250 materials, as well as of various building components and systems. The book has not been referred to in its entirety, but rather at selective parts that consist of window and facade system environmental ratings, namely in pages 36 and 37. More specifically, climate change, ozone depletion, minerals extraction, costs, recyclability and other ratings were used as evidence in the introduction of the thesis, where the current problems associated with curtain wall glazing are discussed and reasons for proposing an alternative, multi-material detail are presented.

[5] Andrasek, A., 2012. Open synthesis// toward a resilient fabric of architecture. *Log 25*, Summer 2012, pp.45-54.

The main claim of the passage is that with an ever-increasing access to computational resources, architects can bypass tired notion of typology, style and metaphor and engage directly with matter and its structure. The article starts off by claiming that the present-day abundance of data and proliferation of coding are having a large impact on disciplines like biology and physics and as an extension architecture. It then goes on to give an explanation of neighbourhood-based computing and multi-agent systems and eventually argue for incorpo-

rating randomness in design computation, as well as for the synthesising of data producing a flexible type of architecture. The article is useful in referencing parts of the text where a larger claim is made of design nowadays being performed on the scale of matter directly. In addition, the use of multi-agency as a design method will be used in the literature review and to argue for the inappropriateness of the technique, as it does incorporate physical material properties, while the multiple scales of operation of the algorithms and the complexity that is promised theoretically does not result in an evident and visible intricacy in the design resolution.

[6] Armstrong, R., 2014. 3D printing will destroy the world unless it tackles the issue of materiality, *Architectural Review*, [online] Available at: http://www.architectural-review.com/home/products/3d-printing-will-destroy-the-world/8658346.article [Accessed 11 November 2014].

Described in the article are the potential risks and pitfalls of the ubiquitous use of 3D printing in the near future, as well as the need for rethinking the nature of materials used in additive manufacturing in order to avoid this from taking place. Armstrong initially mentions the capabilities of emerging manufacturing technologies and then goes on to suggest that these will potential have hugely negative impacts on an ecological level, unless the supply chains and energy requirements of 3D printing are analysed more deeply and the materials utilised made to have lifelike qualities. There is also reference to the materialist philosophies of Latour, Barad, Harman, Morton and Bennett as examples of 21st century conceptions of materiality that move away from obsolete historical notions of it. The article is very useful as a reference for making a point that materiality is not considered in additive manufacturing at the moment and that it needs to become a much more central design consideration. A potential deviation, however, is that the article suggests novel forms of ‘alive’ materials as a solution while the research theme explores the idea of simulating material properties in order to avoid material distribution conflicts, as well as organising materials in space in an informed manner.

[7] Autodesk Maya 2013 Online Docs, 2013. *Types of fluids*. [online] Available at: <http://download.autodesk.com/global/docs/maya2013/en_us/index.html?url=files/Modifying_fluids_Change_dynamic_fluid_behavior.htm,topicNumber=d30e440674> [Accessed 29 December 2016].

This webpage is part of the online documentation for the software Maya and provides information about the three types of fluid effects that can be found in the program. These consist of dynamic fluids that use mathematical equations to compute the flow of liquids, non-dynamic fluids that are less memory-intensive and are based on the use of textures to direct the behaviour of a fluid, and lastly oceans and ponds that are essentially NURBS planes that have shaders or solvers applied to them to give the impression of liquidity. The part that is explaining the computational structure of dynamic fluids is quoted in Design Study 01 in the thesis to provide information about the type of simulation utilised initially.

[8] Autodesk Maya 2015 | Help, 2015. *Fluid output mesh attributes*. [online] Available at: <http://help.autodesk.com/view/MAYAUL/2015/ENU/?guid=GUID-630D5460-8AF0-4BC7-BDFF-20BA63E6C97E> [Accessed 03 May 2017].

This webpage is part of the online help documentation for Maya 2015 and provides information about converting a fluid generated in the program to a mesh geometry. Of a number of parameters that can be controlled, such as the resolution of the output mesh, the colour, opacity, velocity, incandescence and Uvw values that can be assigned per mesh vertex, of relevance to the thesis is the description about colour and opacity data assigning. The information about the latter has been used as a quote in subchapter 6.3.3.3. of the conclusion, where the colour data transferring from the fused particle systems to the mapped mesh is described.

[9] Bader, C., Kolb, D., Weaver, J. C., and Oxman, N., 2016. Data-driven material modelling with functional advection for 3d printing of materially heterogeneous objects. *3D Printing and Additive Manufacturing*, 3 (2), pp. 71-78.

In this journal article Bader et al. present their data-driven material modelling approach to 3D printing multi-material parts with variable properties. They start off by discussing the current limitations of conventional voxel-based 3D printing that due to data volume size restrictions

does not allow the production of high resolution parts, and they then go on to present their own computational technique of working with external geometric data like meshes, point-clouds and vector fields that can be incorporated as the main design element during 3D printing. The article is very technical in nature, and has mainly been used as a reference in the literature review of the thesis, where the work of other academics and researchers in the field of multi-material design is discussed. The main critique posed in effect is that in most of these approaches material behaviour is not considered when designing or fabricating a multi-material element.

[10] Baerlecken, D. and Wright, K., 2014. Nominalized matter: agency of material. *International Journal of Architectural Computing*, 12 (3), pp. 339-356.

The authors describe their textile techniques for generating designs that combine aesthetic, structural as well as ornamental qualities under a single construct. Initially, they discuss Gottfried Semper's metabolism thesis on material transformation and then go on to describe a series of student design exercises that deal with lacing, knitting, combing, 'wettening', felting and weaving. The relevance to the thesis is the claim that the authors make about taking a design approach that is based on generation of form through materials influenced by fields and forces, rather than a preconceived notion of form. This approach has similarities with the design thesis, but at the same time it will be useful in specifying how the thesis takes a different course and moves away from a mere material-agency based approach and towards a hybrid model of agency and design control.

[11] Benjamin, M., Toumi, H., Ralphs, J. R., Bydder, G., Best, T. M. and Milz, S., 2006. Where tendons and ligaments meet bone: attachment sites ('entheses') in relation to exercise and/or mechanical load. *Journal of Anatomy*, April 2006, 208 (4), pp. 471-490.

The article consists of a detailed scientific analysis of the relation between the structural characteristics, function and form of the enthesis attachment site between muscle and bone. What is described in further detail is the adaptation of the enthesis to mechanical stress, the contribution of surrounding tissue to its structural behaviour and lastly the factors contributing to the development of enthesopathies. Although using scientific language to a large extent, of particular value to the thesis is the part of the article that discusses the anchorage and stress dissipation function of the enthesis. Mechanisms such as interdigitation, flaring out, tissue 'scalloping' and gradual bending of the collagen fibres when they attach to the bone surface all contribute to the effectiveness of the connection. The idea is that these mechanisms will eventually inform the design studies of the cladding to structure interfaces. More specifically, they will inform the structuring and formation of the different materials in their point of fusion within the functionally graded materials utilized in the design.

[12] Bennett, J., 2010. *Vibrant matter: a political ecology of things*. Durham; London: Duke University Press.

The main argument in Vibrant Matter is that there needs to be a shift from the understanding of matter as inert and passive, to a livelier concept of it as active vitality. The author uses references from a broad range of philosophical thought looking into the subjects of matter and live force, as well as analysing matter as an assemblage, in its edible form, as metallic substance, in stem cells and as a political ecology. The point made is to rethink the concept of an anthropocentric pyramid of the distribution of life, to a horizontally distributed series of material relations in which humans are equally participating as any other material formation. The book is useful to the research topic as through an in-depth philosophical analysis, it establishes what a vibrant materialist would call a continuous vortex-like field of matter striving to enhance its vitality. This provides another take on the idea of what is continuous. The main limitation is that all the above is analysed solely through a theoretical point of view not really incorporating any architectural discussions on the matter. Although not of a direct relevance to the practical part of the research the book will, however, provide concrete theoretical arguments on the idea of continuity.

[13] Bergson, H., 1998. *Creative evolution*. New York: Dover.

This seminal philosophical treatise consists of an analysis of Bergson's version of orthogenesis, as a replacement of Darwin's theory of evolution. The core concept put forward in effect is that of the élan vital, as a vital force behind morphogenesis and the creative impulse in general. The main emphasis of the book is on vital materialism, which is a different branch of

materialism to the one explored in the research. Some of the parts discussing the philosophy of becoming, however, as well as the interpretation of modern science by Descartes, and Leibniz have been relevant to the concepts of measurable and inert matter that have been critiqued in the thesis. In addition, the book has been used as a reference in the introduction where a basic literature review of contemporary materialist theories is presented.

[14] Bergson, H., c1998. *Matter and memory*. New York: Zone Books.

Bergson discusses in this book the relation between body and spirit and analyses the various philosophical takes on the relation between the two. The main idea put forward is the one of matter as image that is more than representation, but at the same time less than a thing. This effectively means that perception is synonymous to the sensing of images, and that this is essentially how one apprehends the external material world. This discussion of how matter is perceived by one's mind has been touched upon in the Thinking with Blends part of the thesis, namely in subchapter 4.3.2., where the way that material (termed mental materials in that instance) perception operates is discussed. Although there was not direct expansion and reference to Matter and Memory at that part of the thesis, the book was used as a reference in the materialist theory literature review in the introduction.

[15] Bhabha, H., de Loisy, J., Rosenthal, N. and Royal Academy of Arts, 2009. *Anish Kapoor*. London: Royal Academy of Arts.

This is a catalogue that followed the Anish Kapoor exhibition held at the Royal Academy of Arts in September 2009. The book contains essays from several art critics and philosophers who discuss the work of Kapoor from a cultural, historical and psychological theory perspective. Although the essays are limited in extent there are some very relevant and pertinent issues discussed that address ideas of materiality, self-generation of form and the interrelation of physical and void space. More specifically, the analysis of the highly materially-based work of the artist through the reciprocal relation of the Sanskrit terms Svyambhuv and Rupa (standing for self-born and man-made), has a direct application to the proposed hybrid design methodology. Additionally, the relation of the container and the contained, based on Heidegger's parable about the "Thing", will also feed into an in-depth analysis of containing geometry and simulated material within, in the design process.

[16] Bharti, I., Gupta, N. and Gupta K. M., 2013. Novel applications of functionally graded Nano, optoelectronic and thermoelectric materials. *International Journal of Materials, Mechanics and Manufacturing*, Vol. 1, No. 3, August 2013, pp. 221-224.

The paper compiles ongoing researches in future applications of new types of Functionally Graded Materials and assesses the performance impacts these might have on respective technologies. Following an initial explanation of the properties of FGM, the authors outline the uses of CNT reinforced metal matrix functional graded composites and explain their advantages through the analysis of their application in a thermoelectric material. The article is useful, firstly in terms of providing background knowledge for the material analysis part of the thesis and secondly in informing the design studies particularly with the part that explains the different types of FGM according to the nature of the gradient. Any limitations in regard to how useful the article is have to do with the fact that it comes from the field of engineering, although to a very large extent it does eschew the use of scientific terminology.

[17] Birman, V. and Byrd, L. W., 2007. Modeling and analysis of functionally graded materials and structures. *Applied Mechanics Reviews*, 60(5), pp.195-216.

This scientific research paper consists of a review of current (in 2007) developments concerning technical applications and theory of functionally graded materials. It starts off with a general review of fgm, and then goes on to discuss heat transfer, stress and deformation analyses techniques, optimisation, testing, and examples of applications of graded materials. The article is to a large extent incomprehensible due to the scientific nature of the contents, however, it has been useful in a. providing an overview of current applications and uses of multi-materials, and b. in providing evidence of the existence of glass/alumina and alumina/aluminium functionally graded materials. Point a. will be used in the introduction of the thesis and point b. in the main design subchapter where the sub-materials that will be fused together in the simulation are discussed.

[18] Blaney, A., Alexander, J., Dunn, N., Richards, D., Rennie, A., and Anwar, J., 2017. Directing self-assembly to grow adaptive physical structures. *International Journal of Rapid Manufacturing*, 6(2-3), pp.114-133.

This paper consists of the authors' attempts of building variably material property aggregate structures by electrolysing saltwater in a controlled manner. It starts off by mentioning the relevance and potential use of this research in architecture and design, followed by a description of the set out of the physical experiments, a presentation of the results, and a discussion of the findings. Although the methods followed over the course of the experiments are rigorous, the multi-material results attained seem to still be at an initial stage. The paper has been used as a reference in the literature review, of multi-material design research taking place currently.

[19] Bleakley, I., 2016. *Curtain wall structural analysis*. [email] (Personal communication, 27 January- 02 June 2016).

This email correspondence has been with Senior Facade Engineer Iain Bleakley of AKT II Envelopes and was concerning the structural analysis of a typical curtain wall glazing panel. Included in the correspondence is a stress analysis of the structural frame of the panel, a stress and displacement analysis of the glazing, a load analysis of the brackets that are connecting the panel to the floor slab, as well as information about the typical conditions input in the analyses, what the results show and what are the appropriate ways to correspond to these results from a material point of view. The analyses and discussion have been invaluable in understanding the forces and loads operating on a panel and enabling an informed decision making process to take place in terms of the set out of the simulation in the main design, as well as an evaluation of material distribution afterwards.

[20] Bogner, D. and Noever, P. eds., 2001. *Frederick J. Kiesler: endless space*. Vienna: MAK.

The book consists of a series of articles, conversations, chronology and manifesto (on correalism) that summarize Kiesler's work and concepts of continuity and endlessness and that attempt to situate it in relation to contemporary discourses about digital design. Each of the articles explores this relevance through a technical, social or spatial perspective, with one of the main arguments being that the understanding of the human subject, driver of Kiesler's architecture and interlinked with Lacan's and Freud's theories of the unconscious was in many ways drastically different to the contemporary subject that is "ambiguous in its definition and psychological structure". On a more technical level it is argued that Kiesler's work was merely propositional in the sense that it never reached the geometrical precision available by today's digital tools. The relevance of the subject lies in its direct link to the idea of continuity as an interdisciplinary, "biomorphic" set of relations held together in continuous tension. The extent to which Kiesler's ideas are discussed is limited. Some of the concepts nevertheless are useful in extending the concept of continuity to a discussion about inhabitation and beyond the current material based approach.

[21] Bragg, W., 2004. *Concerning the nature of things: lecture VI, the nature of crystals: metals*. [online] eBooks@Adelaide, The University of Adelaide Library. Available at: https://ebooks.adelaide.edu.au/b/bragg/william_henry/nature-of-things/chapter6.html

The 6th of a series of lectures that the author delivered at the Royal Institution of Great Britain, in which he explained the science behind gases, liquids, diamonds, ice and snow and metals. The lecture starts off by describing the atomic structure and crystalline arrangement of indicative metallic materials, illustrated by a series of rather compelling microscopic x-ray images and then goes on to analyse the effect that metal alloying has on the bonds between the atoms of two materials and how these bonds affect ductility, flexibility and other properties. The latter is an area of exploration related to multi-materials, with the initial idea for reading the article being to use this in order to back up the claim of materials and alloys crystallising naturally in their liquid state. Although information on this claim was not part of the article, it has at the same time provided useful information on the science behind the bondage of two materials on a micro-scale. An obvious limitation is that the science described is from the 1920s, which is to a large extent now obsolete.

[22] Brookes, A., c1998. *Cladding of buildings*. London; [New York]: E & FN Spon.

Addressed in this book is the theme of building envelopes, namely the different types of light-weight cladding. The contents are structured around the various materials that can be used in a building facade that consist of concrete, terracotta, bricks, metal, glass, and timber among others. The main part of the book that has been referred to and is of particular relevance to the PhD is the chapter focusing on the use of curtain wall glazing in buildings and the discussion on what these are, the different types of glazed envelopes, their fire resistance properties, and the various problems associated with them. The definition of what a curtain wall glazing is has been used in the introduction of the book, namely in subchapter 1.6.1.

[23] Capra, F., 1996. *The web of life: a new synthesis of mind and matter*. London: HarperCollins.

The author argues in this book, about a shift from a Cartesian mechanical conception of material and life to one that is systemic and ecology-related. It starts off by providing a historic overview of the relation between mind and matter and the different stages that this has gone through from a theoretical and philosophical perspective. The author then goes on to discuss how these two terms have ended up being reciprocal and entangled through an analysis of cybernetics and systems theory and concludes by discussing how this ecological view of life needs to become much more widespread. There is a multitude of themes, ideas and references that are directly relevant to the thesis that have to do with the historical overview that can be used in the introduction, the multiple realizability fallacy that will be referenced into the main thesis, the epistemology of simulation, the fact that life has evolved through processes of blending and structural coupling, and most importantly the difference between brain and mind, as well as Varela's description of the "Cartesian anxiety."

[24] Carpo, M., 2011. *The alphabet and the algorithm (Writing Architecture)*. Cambridge, Mass.; London: MIT Press.

Described in the book is the so-called allographic way of creating a building that was established by Alberti in the Renaissance, which having gone through its modernist reincarnation is now according to Carpo beginning to come to an end. The author starts off by analysing the principle of identicality that has been so pervasive of modernism and then goes back to early Humanism and to Alberti inventing a notational system in order to digitize building information and "transmit" it to builders without the need for mediation. This separation of the designer and the builder, the latter restricted to a mere reproduction of the architect's intent, is now changing through the use of digital technologies into digital craftsmanship resembling pre-modern artisanal making and giving rise to variability and participatory authorship. This conversion of allography to autography has been used as the main argument in the paper "Translating Digital to Physical Gradients" and also as a theoretical backdrop in the fabrication end of the design methodology. It is effectively very useful in highlighting how this shift can/will find its natural output into multi-material construction, with the ease of this method of constructing enabling the architect as builder even further.

[25] Carpo, M., 2014. Breaking the curve. *Artforum*, February 2014, pp. 168-173.

The article consists of a historical description of the turn from architectural modernity into a post-modern, post-scientific condition. Carpo starts off by explaining the invention of spline modelling in the late 1950s and its usage in architectural design all the way up to recently, when it has started to be replaced by voxel modelling, finite element analysis and simulation design procedures. According to him, this is a result of and reflected by the change in the scientific paradigm from the necessity to extrapolate mathematical rules and models as a tool of simplification to the existence of big data nowadays that allows for information to be stored, replicated and retrieved in a one to one manner. This is very useful in contextualising the use of simulations within a wider shift towards the use of new tools in digital design, as is the part that describes the relation of the discreteness of nature and material to the subdivision-based contemporary design tools. A limitation is the short extent of the article.

[26] Carroll, S. B., 2007. *Endless forms most beautiful: the new science of evo devo and the making of the animal kingdom*. London: Phoenix.

The book consists of an in-depth analysis of the way genes generate the genetic blueprint of organisms and how they eventually regulate their resulting form. The author starts off with an analysis of the architecture of animals, and then discusses the function of genes as genetic switches that turn on or suppress certain developmental features during embryogenesis in order to produce different formal organismic outputs. He then puts forward the thesis that there is a genetic toolkit that is to a large extent invariant, with differentiation being a result of the existence of these genetic switches. Although not directly central to the thesis per se, the book contains thorough scientific analysis that explains the fact that form follows a mathematical and sequential series of genetic events that unfold over time, which is something that can be used as evidence when arguing against a top-down approach to form generation.

[27] Catts, O. and Zurr, I., 2013. The vitality of matter and the instrumentalisation of life. *Architectural Design*, Volume 83 Issue 1, pp. 70-75.

The article describes the work of artists Catts and Zurr, concerned with synthetic biology and the creation of semi-living prototypical installations. The authors begin by pointing out the shift in biology from being merely analytical to nowadays having synthetic capabilities, explaining through historical, fictional and scientific examples the ability of biological engineering to convert life into a raw material. They then go on to describe their work that challenges notions of what living matter consists of and what people's empathy is towards it. The article's relevance is the description of matter being attributed with vitality and agency, which are concepts that can inform the definition of continuity in the thesis. The concept of gradients of life of materials can also relate to the part of the research describing a potential extension of the capabilities of FGM to interact with the surroundings.

[28] Coole, D. H. and Frost S. eds., 2010. *New materialisms: ontology, agency, and politics*. Durham, N.C.: Duke University Press.

This very informative and useful book consists of a collection of essays by several scholars that provide their own takes regarding the shifting definitions of what materials and materialism are in a contemporary setting. The main point of the authors in effect, is to demonstrate how advances in science and contemporary theoretical discourse are influencing traditional readings and takes of what the material world is and consists of. The editors' introduction is a very succinct and informative take on this, with several parts from it used as key references in various parts of the thesis. Additionally, Jane Bennett's essay on vital materialism and Pheng Cheah's one on the writings of Derrida about non-dialectical materialism have also been used in order to highlight the different approaches to the more general term of materialism.

[29] Corbellini, G., 2008. *Bioreboot: the architecture of R&Sie [n]*. Milano: 22 Publishing.

The book consists of a catalogue of the office's projects, an introductory text that outlines the theoretical basis of the work and concludes with a conversation between members of the practice. The intellectual underline relates to issues of an open source algorithmic approach to non-linear framework design that is coupled with an agenda of narrative. Ecology and nature are also key aspects of the design process that provide an opportunity to structure narrative rather than be looked into from a performance related or sustainability point of view. Its relevance is on a theoretical level, providing an alternative way of looking into nature where complex, open-ended relations can enable unexpected or the condition of 'endlessness' to occur, moving this way away from common discussions about emergence.

[30] DeLanda, M., 1995. Uniformity and variability: an essay in the philosophy of matter. In: Netherlands Design Institute, *Doors of Perception 3: On Matter Conference*. Amsterdam, Holland 7-11 November 1995. [online] Available at: <http://museum.doorsofperception.com/doors3/transcripts/Delanda.html> [Accessed 29 April 2013].

This article by DeLanda published back in 1995, makes a vital point about the cultural, social, and philosophical implications of matter as a uniform entity and its counterpart, matter in continuous differentiation. It starts off by discussing the development of the philosophy of matter from ancient Greece all the way to the present day, then goes on to discuss Deleuze's machinic phylum concept of matter-energy that is in flux, the homogenization of materiality and dilution of skills taking place in modernism and concludes by arguing for the relevance of reinstating variable materiality in philosophical discourse. These have an obvious and essential relevance for the thesis, and quite a few parts will be quoted when discussing the curtain wall materiality in the corresponding chapter, in the introduction discussing hylomorphism and possibly in other parts where the multi-material design thesis is described.

[31] DeLanda, M., 2002. *Intensive science and virtual philosophy*. London: Continuum International Publishing Group Ltd.

This seminal book is essentially a clear and precise take on Deleuze and Guattari's philosophy and ideas on ontology. It consists of four main chapters dedicated to mathematics, the relation of the virtual to space, as well as its relation to time, and lastly its links to the laws of physics. The book is very helpful in elucidating quite a few Deleuzian concepts regarding the topological structure of the abstract virtual space of ideas and the trajectories that emanate from it becoming intensive and effectively of a "specific" nature. Parts that discuss ideas of equilibrium as they relate to systems theory, will be used in making a point in the literature review about the appropriateness of particle systems as a design tool. In addition, and more importantly, other parts will be very useful in sustaining the thesis of perceiving the method proposed in terms of a flow of relations, as opposed to a form-centric understanding that focuses on the artefacts produced during the process.

[32] DeLanda, M., 2002. Philosophies of design: the case of modelling software. In: J. Salazar, R. Prat, A. Ferre and M. Gausa, eds. 2002. *Verb: Architecture Boogazine*. Barcelona: Actar. pp.132-142.

This very useful article consists of an analysis of the two prevalent theories regarding the generation of form and of advanced CAD software corresponding to the theory argued for by the author. More specifically, the first philosophy of design discussed concerns the idea of pre-existing form being projected upon the material world, while the second regards matter and energy as equal participants in the emergence of form. Favouring the latter DeLanda goes on to discuss the concept of the machinic phylum put forward by Deleuze and then appropriate design software that allow for materiality to have an equal contribution to form generation. Interestingly, the spline and NURBS surface is included in these new types of software, while there is a part dedicated to particle systems as another type. The obvious parallels to the research will be discussed in the thinking with blends chapter of the thesis.

[33] DeLanda, M., 2011. *Philosophy and simulation: the emergence of synthetic reason*. London: Continuum International Publishing Group Ltd.

In this book DeLanda analyses the different types of simulations that exist currently, ranging from cellular automata to genetic algorithms, neural nets and multi-agent systems. The contents are structured starting from more basic forms of simulation such as what is termed the 'prebiotic soup' and increase in complexity to mammalian memory and primitive language. The main relevance of this publication to the research are the various analyses of the epistemology of computer simulations, namely what makes the results of a simulation valid and what is the acceptable degree of adherence to physical reality. These have been used in the fusion design studies in the thesis, where the structuring and validation of the material fusion simulations are discussed.

[34] Deleuze, G. and Guattari, F., 2004. *Thousand plateaus: capitalism and schizophrenia*. London: Continuum International Publishing Group Ltd.

This book is part of the authors' larger philosophical work termed Capitalism and Schizophrenia and is an analysis of a wide range of social, cultural and philosophical phenomena and debates at the time. The contents are presented in a characteristically non-linear fashion with a very large number of topics (or what the authors term as 'plateaus') being analysed that range from music to animal behaviour and to political economy among others. Amongst these, of particular relevance to the thesis are the chapters where the body without organs, as well as the machinic phylum and hylomorphism are discussed. Small parts of these have been used as references in the introduction, namely in the part where the theoretical aspects of materiality and the specific take of the thesis to that are presented.

[35] Dezeen Limited. 2013. *Print shift- how 3D printing is changing everything*. [Print-on-demand publication]. London: Dezeen.

This print on demand magazine published by Blurb and the design blog Dezeen, is a compendium of the various applications of and the fields that the rapidly advancing 3D printing technology is starting to have an impact on. These fields are namely food, fashion, design, and architecture. Of particular usefulness is the part addressing the emerging practice of utilising 3D printing in the construction of buildings that is beginning to take place in China and elsewhere.

Additionally, the works of architects such as Neri Oxman that are featured in the magazine has been referred to as part of the literature review in the field of multi-material printing. Although these have not been used directly as references in the thesis, the magazine has nevertheless been a useful source of information about the state of contemporary additive manufacturing practice.

[36] Dierichs, K. and Menges, A., 2012. Functionally graded aggregate structures: digital additive manufacturing with designed granulates. In: ACADIA 12: Synthetic Digital Ecologies, *Proceedings of the 32nd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*. San Francisco, USA 18-21 October 2012. San Francisco: California College of the Arts.

This article discusses the use of loose granulates as an alternative to additive manufacturing and how these can be employed in constructing aggregate structures. It starts off by providing a succinct overview of previous use of aggregates in architecture, and then goes on to argue about their benefits, followed by a rather abrupt technical discussion about the practicalities of simulating aggregate behaviour through particle systems, as well as ways that these can be fabricated physically. The intent of functionally grading the aggregates seemed to be relevant to the research initially, however, the corresponding part in the article remains rather vague and did not provide any additional information on material gradation.

[37] Diethelm, J., 2012. *Conceptual blending and integration in design thinking*. [online] Available at: http://pages.uoregon.edu/diethelm/Conceptual%20Blending%20and%20Integration%20in%20Design%20Thinking.pdf [Accessed 10 August 2016].

Discussed in this brief article, is the idea of conceptual blending and how it is unconsciously utilised in designing. The author starts off with a short summary of what conceptual blending is, stating that double-scope integration is the idea of blending in its highest level and then continues by giving a very loose impression of how this is used in metaphoric language. Although the claim is that blending will be discussed in relation to design, this does not really happen and the text is restricted in merely posing some basic questions about how one's understanding of design might be different as a result of being aware of the existence of conceptual blending. The article is not directly usable mainly due to its limited extent and shallowness, however, it does provide some very basic information about blending theory that could be useful in understanding the principles slightly better.

[38] Doddamani, M. R. and Kulkarni S. M., 2012. Flexural behavior of functionally graded sandwich composite. In: F. Ebrahimi, ed. 2012. *Finite element analysis- applications in mechanical engineering*. [e-book] Publisher: InTech. Available at: <http://www.intechopen.com/books/finite-element-analysis-applications-in-mechanical-engineering> [Accessed 07 April 2014].

In this paper Doddamani and Kulkarni describe the fabrication and mechanical property measurements of a sandwich composite element consisting of a functionally graded core and a jute fibre skin. The authors introduce the advantages of the use of functionally graded materials, describe their objective of fabricating a composite material consisting of a rubber and fly ash graded core with layers of fibre attached to the core with epoxy resin and then analyse the properties of the composite at different consistencies using both experimental and finite elements analyses. They conclude that a higher concentration of rubber versus ash, achieves better results in modulus and strength of the composite. The paper is useful for the materials chapter of the thesis and namely for the part where the relevance and usefulness of functionally graded materials are described. Although of a technical nature for the most part, the article can also be used to highlight the potential failure of composites and their structural inferiority when compared to FGM.

[39] Doubrovski, E. L., Tsai, E. Y., Dikovsky, D., Geraedts J. M. P., Herr. H. and Oxman, N., 2014. Voxel-based fabrication through material property mapping: a design method for bitmap printing. *Computer-Aided Design*, Volume 60, March 2015, pp.3–13.

In this journal article the authors present their research on a bitmap printing method for multi-material additive manufacturing. This workflow is implemented on the design of a customised prosthetic socket for people with limb loss. Presented in the beginning are the limitations in current design thinking in which form is prioritised over material, as well as in the standardized singular-material designs for prosthetic limb sockets that do not take into account individual 'fitness' conditions. The authors then present a very extensive analysis of their multi-material design workflow for the socket that consists of an MRI scan of a limb, pressure force calculation on the socket and the assigning of differentiated hardness and softness sub-materials in the new part. The article is useful in providing information about the current limitations of multi-material printing, as well as for the literature review part of the thesis in which the benefits of the hybrid-control multi-material design workflow are juxtaposed against other multi-material design techniques.

[40] Drazin, A. and Küchler, S. eds. 2015. *The social life of materials: studies in materials and society*. London: Bloomsbury Academic.

The book consists of a number of essays that discuss the cultural use of materials in different contexts that range from the use of silk in native communities in Mali to the formation of digital material libraries in the pharmaceutical industry. Although rather peripheral to the research subject overall, there are two parts that can be used directly in the thesis. The first one is the discussion about the history of plastics and external agency that brings out the intrinsic properties of these materials and the second is the concluding essay by Susanne Küchler. This provides a very useful overview about the history of material innovation that goes back to the nineteenth century, as well as current examples of digital material libraries in which the properties of different substances can be accessed and hybridised virtually with ones of others materials in order to evaluate the viability of new material innovations. This latter part can be used in the discussion about the use of material fusion simulations as a way of pre-working out the spatial and organisational behaviour of material.

[41] Ednie-Brown, P., 2013. bioMASON and the speculative engagements of biotechnical architecture. *Architectural Design*, Volume 83 Issue 1, pp. 84-91.

The work of Ginger Krieg Dosier and Michael Dosier of Vergelabs is discussed through examples of their ongoing research on building materials consisting of biological elements. The author starts off by placing the work of Vergelabs within the wider nascent field of biotechnical architecture (namely by mentioning research projects by Rachel Armstrong, Mitchell Joachim and Magnus Larrson) and then goes on to describe projects such as 3-D bio-printing and materials such as the biomanufactured brick and glowcrete. This work is discussed through the idea of the avant-garde as a tradition that has nowadays become part of the everyday, with the research of Vergelabs illustrating this through the physical actualisation of speculative ideas. The use of bio-printing for fabricating non-homogeneous materials is particularly relevant for the literature review of the thesis, while the part that mentions the embedding of scaffolding or structural elements within a material can be used for illustrating further applications of functionally graded materials.

[42] El-Hadad, S., Sato, H.; Miura-Fujiwara, E. and Watanabe, Y., 2010. Fabrication of $Al\text{-}Al_3Ti/Ti_3Al$ functionally graded materials under a centrifugal force. *Materials*, 3 (9), pp. 4639-4656.

In this article El-Hadad et al. discuss their novel reaction-centrifugal-mixed-powder-method (RCMPM) for manufacturing functionally graded materials consisting of aluminium and titanium aluminide. Described initially are existing centrifugal casting techniques for fabricating FGM, which namely are centrifugal solid particle, in-situ and mixed-powder methods. These are accompanied by diagrams that illustrate the processes in a concise and clear manner. Following a series of tests using different temperatures for the molten substances, the authors conclude that affecting the hardness of the FGM parts are the particle shape and size, as well as their distribution gradient that are all controlled in their turn by temperature variations of the poured materials. The article is valuable to the thesis in terms of extracting parameters of the densities and temperatures of the molten substances, as well as centrifugal force values in order to inform the digital material simulation studies. It is also useful in showing the validity of conducting liquid material simulations (for design research with FGM), as this is already the case with existing manufacturing technologies.

[43] EOS (e-Manufacturing Solutions), 2014. *EOS and Airbus Group Innovations Team on aerospace sustainability study for industrial 3D printing*. [online] Available at: < https://www.eos.info/eos_airbusgroupinnovationteam_aerospace_sustainability_study> [Accessed 05 January 2017].

Described in this online article is a study that compares the environmental impact of a conventional welded nacelle hinge to one that has been 3D printed. This research project was a collaboration between the company EOS and Airbus, and it concerned a detailed cradle-to-cradle analysis of the parts, including the manufacturing processes, type of material used, energy required for extracting the initial raw powder metal, waste produced in the process, and summary of the results. The latter showed that there was a significant reduction in the weight of the part and in the carbon dioxide emissions over its total lifecycle that were reduced by 40%. This will be used in the introduction of the thesis, where the assimilation of 3D printing in the aerospace industry and the benefits of this are discussed.

[44] EPDM Roofing Association, 2003. *EPDM Membrane Production: Materials and Manufacturing Processes*. [pdf] EPDM Roofing Association. Available at: < http://www.epdmroofs.org/attachments/epdmmembraneproductionmaterialsandmanufacturing-processes_era.pdf> [Accessed 26 November 2016].

This technical online article contains an extensive summary of the production process of EPDM membranes. It starts off by outlining the raw materials used in EPDM production and continues by providing a description of how these are manufactured individually. It then goes on to explain how these materials are mixed and how the resulting membrane is produced, as well as to discuss in the end how the various properties of the EPDM membrane relate to the materials and manufacturing methods used for producing it. This is going to provide information and evidence about the toxicity and low environmental sustainability of the process, which will be used in the cladding subchapter of the thesis where the various problems associated with curtain wall glazing are discussed.

[45] Excell, J., 2013. *The rise of multi-material 3D printing*. [online] Available at: < https://www.theengineer.co.uk/issues/may-2013-online/the-rise-of-multi-material-3d-printing/> [Accessed 05 January 2017].

This online article is one of very few invaluable to the research sources that discuss the state of multi-material printing currently and its near future outlook. It starts off by discussing the practice of customising variable material properties within a single part, and then goes on to briefly mention the potential benefits that this manufacturing technology has in comparison to single material printing. It then discusses the current state of technology and the various limitations that are summarised by the fact that the problem with opening up the palette of materials is the viscosity of various substances and their capacity to pass through the 3D printing nozzles and to cure in an adequate time. As mentioned, the article is critical in providing information about developments in multi-materiality and parts of it will be used as quotes to indicate the timescale towards ‘real’ multi-material application. Of additional interest is the passage discussing the embedding of electrical circuitry within a single multi-material components in the near future.

[46] Fauconnier, G. and Turner, M., 1998. Conceptual integration networks. *Cognitive Science*, 22(2), pp.133-187.

In this article, Fauconnier and Turner present an extensive analysis of their cognitive theory of conceptual blending. They start off by providing a description of what a conceptual integration network consists of, followed by various applications of this model in practice, the main principles that characterise integration networks, and lastly what they describe as additional dimensions of their model. This paper has been a key reference to the research, mainly as far as the structural aspects of the theory are concerned and the parts where the main framework and underlying structure of conceptual integration networks are analysed. These have been used in several parts of the thesis, mostly in the Thinking with Blends chapter and the Visualising Fusion subchapter.

[47] Fauconnier, G. and Turner, M., 2002. *The way we think: conceptual blending and the mind's hidden complexities*. New York; [Great Britain]: Basic Books.

This book contains Fauconnier and Turner's extended thesis on their cognitive theory of conceptual blending. The authors start off by discussing what conceptual networks actually are, how their use has contributed to a human cognitive revolution of some sort and what are the main constituents of blending operations. They then go on to give an extensive presentation of various types of blending networks, their use in everyday language and thought and how these are structured in the human mind. Various parts of the book are fundamental to the PhD thesis, and will be primarily utilised in the main chapter discussing the blended thought process that takes place during the multi-material design workflow, as well in the visualisation chapter where a similar mental operation is in effect. The main aim overall will be to demonstrate the inextricability between conceptual blending theory and the computational blending design methodology.

[48] Federal Institute for Research on Building, Urban Affairs and Spatial Development within the Federal Office for Building and Regional Planning, 2011. *Graduated building components: Production procedures and areas of use for functionally graduated building components in construction*. Berlin: Federal Ministry of Transport, Building and Urban Development.

The article is in a magazine published by the German ministry of transport, building and urban development that consists of research projects funded by the government as part of the Zukunft Bau initiative for innovative technologies that can be adopted by the construction industry. As the initial part of the article states, the objective of the research is to explore the transferring of the idea of the functional gradation of materials from the aviation and space travel industries into building construction. Following a brief explanation of the benefits this might have, the authors outline their tests on creating graded concrete, textiles and foam elements. What is of very high value to the thesis is among others, the latter part of the article where the intent of the authors to extend the palette of seamlessly joined materials is stated. This ongoing research is conducted by the Institute for Lightweight Structures and Conceptual Design at the University of Stuttgart and is also useful for proving that the architectural application of FGM is being researched into on a formal, government-run level due to the material saving, efficiency and energy-related advantages that it can potentially have. The limitation of the article is that only an outline of the research is presented and not any in-depth studies.

[49] Foucault, M., 1967. Of other spaces. *Diacritics*, 16(1), pp.22-27.

This essay that is based on a lecture given by Foucault in 1967, consists of the author's description of his ideas on heterotopias. He starts off by describing these as being different to the non-real space of a utopia and explains how they form counter-sites that reflect conventional social spaces. He then goes on to give a series of examples of these sites, which include boarding schools, cemeteries and Jesuit colonies, followed by a description of the two categories and five principles that make up a heterotopia. Of particular relevance to the thesis is the third principle according to which imaginary and sometimes incompatible spaces can be juxtaposed and overlapped on one that is real. The example used to show this is the Oriental garden, while this principle will be used to illustrate further the application of conceptual blending theory in the design.

[50] Fratzl, P., 2007. Biomimetic materials research: what can we really learn from nature's structural materials? *J. R. Soc. Interface*, vol. 4, no. 15, pp. 637–642.

The article analyses the relation between structure and function in nature and compares it to material practices in engineering. The author goes on to extrapolate principles found in nature, namely use of limited material elements, growth and adaptation, hierarchical structuring as well as self-repairing and healing and compares that to the rigid and redundant man-made fabrication processes. He also suggests that for a successful translation of naturally occurring principles into material science to take place there needs to be a closer understanding of the problems and constraints that material formation in nature responds to. It concludes that it is essential to adopt an interdisciplinary approach of creating databases of acquired knowledge about bioprocesses, as well as a new approach to the dissemination of that knowledge. There are instances in the article where form, structure and function are seen as a continuous whole of interrelations that can provide practical arguments for the research on continuity.

[51] Galjaard, S., Hofman, S., Perry, N. and Ren, S., 2015. Optimizing structural building elements in metal by using additive manufacturing. In: IASS (International Association for Shell and Spatial Structures), *Future Visions: Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2015*. Amsterdam, The Netherlands, 17-20 August 2015. Amsterdam: IASS.

This technical article is describing the use of topology optimisation and additive manufacturing to fabricate the steel nodes of a tensegrity street lighting structure in The Hague. The authors begin their description of the design operations by outlining the reasons that they turned into 3D printing for this specific node detail (the main one being that there had to be a thousand nodes), then discuss the three main parameters of their endeavour, namely the design features, CAD tools employed, and the ideal properties of the material to be used, and then expand on the topology optimisation routine that was followed. Outlining the pros and cons of their approach in terms of costs, ease of the digital design process, and material performance, the article is useful in providing information on a similar scale of operation to the one in the design thesis. It will be used in a footnote in the main design subchapter as an example of an alternative design route for creating openings and reducing the material in the inner pane of the curtain wall glazing connection.

[52] Gengnagel, C., Kilian, A., Palz, N. and Scheurer, F., 2011. *Computational design modelling: proceedings of the design modelling symposium Berlin 2011*. Berlin; Heidelberg: Springer- Verlag.

Although consisting of a diverse range of articles covering very different topics, the usefulness of the book is namely related to two specific articles, one written by Campo and Manninger and the other by Oberascher, Matl and Brandstätter. The former is relevant to the research in that it questions the convention of the seam in architecture, as a moment of transition between different material conditions and instead considers it as "a gradient change in the surface condition." It will provide a. an example of phenomenally seamless building (Shanghai Expo 2010 Austrian Pavilion) that can be questioned in the thesis b. useful references such as Gottfried Semper and DeLanda, who discuss the seam and the uniformity as cultural conditions. The latter article, is a unique example of building in concrete a roof structure that was generated using fluid dynamics and more specifically Realflow. As this software has been used extensively in the design studies of the thesis, the article will be used to critique an inappropriate use of the tool in this case that doesn't consider material properties.

[53] Genin, G. M., Kent, A., Birman, V., Wopenka, B., Pasteris, J. D., Marquez, P. J. and Thomopoulos, S., 2009. Functional grading of mineral and collagen in the attachment of tendon to bone. *Biophysical Journal*, 97, August 2009, pp. 976-985.

This medical research article consists of an analysis of the tendon to bone connection and a description of the mechanisms that contribute to its unique mechanical properties. The authors start off by explaining the tissue morphology of the insertion and then provide a series of mathematical descriptions of the material gradation occurring at that point that mainly have to do with the gradual differentiation of mineral concentration and fibre orientation. Although mainly scientific and therefore consisting of information that is beyond the scope of the present research to assimilate, the starting part of the article, as well as the conclusion, provide useful information in regard to the structure and material organisation of the insertion. This information will be used in the design chapter of the thesis, where the mechanisms employed at an organ level in the enthesis are borrowed to inform parts of the design of the aluminium to glazing connection.

[54] Gervasi, V. R. and Crockett, R. S., 1998. Composites with gradient properties from solid freeform fabrication. In: Laboratory for Freeform Fabrication (LFF) at the University of Texas at Austin, *Proceedings of the Ninth Annual International Solid Freeform Fabrication Symposium*. Austin, USA 10-12 August 1998. Austin: University of Texas.

This article, written by scientists from the Milwaukee School of Engineering, concerns the 3D printing of variable porosity shells into which an epoxy filler material is poured in, in order to generate graded property structures. The authors start off by explaining what functionally graded materials are, they then provide some background information about their Tetracast build style of generating lattice structures, present their objective of building gradient Tetracast parts, and conclude with a series of material tests measuring the elasticity properties of these parts. The article is useful as it provides general information about FGM, as well as what is rare research in physical FGM builds.

[55] Gibson, J.J., 1986. *The theory of affordances*. [online] New York and London: Taylor & Francis. Available at: http://cs.brown.edu/courses/cs137/readings/Gibson-AFF.pdf

In this article, the psychologist James Gibson presents his theory on the perception of the visual environment. What are termed as affordances in this theory, are clues in one's immediate environment that form triggers for a course of action. These do not require sensory processing, but are responsible for causing one to act unconsciously. A variation of this concept has been used numerously in the Thinking with Blends chapter of the thesis, namely when the affordance of materiality is discussed. This concerns the limitations posed by the material's properties and characteristics in terms of how it can be engaged and interacted with, without this interaction causing the material to fail or behave against its natural propensity.

[56] Gleiniger, A. and Vrachliotis, G. eds., 2008. *Simulation: presentation technique and cognitive method*. Basel: Birkhäuser.

The book contains a series of articles and writings on the use of simulation as a design and representation tool in architecture. All articles contain relevant information and references that can be used directly in the thesis, however, of particular relevance is Gramelsberger's article titled "the epistemic texture of simulated worlds." This starts off by providing a brief overview of the history of mathematics that led to the invention of simulations, and then goes on to discuss issues relating to the appropriate resolution of a simulation, the difference between deterministic, partial differential and Monte Carlo simulations, as well as the fact that they are all based on a discretization of reality that is otherwise continuous. This will be used in the concluding end of the thesis where the shortcomings of the particle-based material blending simulations are discussed and will provide vital references that illustrate the various problems of designing with functionally graded materials.

[57] Gonchar, J., 2012. Beauty and the behemoth: SHoP deploys digital technology and imaginative design to give Brooklyn's Barclays Center unexpected civic presence. *Architectural Record*, 200(12), pp.100-104.

In this journal article Gonchar provides a brief analysis of Barclays Centre, an 18,000 seat multi-purpose arena located in Brooklyn, New York. The article starts off with a mention of the main characteristics of the building, a brief history of how it came to be, and a slightly more extensive analysis of the facade that is the main feature of the arena. This, comprised of 12,000 steel alloy panels that were all unique, were modelled digitally, then unrolled and nested to maximise their fit within flat steel panels, and then assembled in large sections on the substructure and then shipped to site. The article does not go into any depth apart from providing basic information about the assembly process, but it will nevertheless be used as a reference in the part of the thesis where the increasingly sophisticated building componentry methods are discussed.

[58] Gordon, J. E., 1988. *The science of structures and materials*. Scientific American Library.

In this book, Gordon proposes and addresses the fact that the study of materials and things on a molecular level can inform one's understanding and design of large scale structures. It also proposes the study of living organisms as a way of generating structures that exhibit optimised material distribution and formal organisation. The contents are organised starting from the study of properties such as strength and stiffness, then the author looks into various structures and examples of tensile failures, and then does a study of various materials both in nature, as well as in a man-made context. Mostly referred to as a source of general knowledge of materials, a quote from the book discussing the homogenisation of materiality has been used in subchapter 4.1.4.

[59] Gosden, C. and Malafouris, L., 2015. Process archaeology (P-Arch). *World Archaeology*, 47(5), pp.701-717.

In this journal article Gosden and Malafouris present their ideas on process archaeology, which "explores modes of becoming rather than being" in the form of three theoretical postulates followed by six positions from shorter to larger time spans. They start off by briefly mentioning the various contemporary materialist theories and the process philosophy that the article is concerned with and then go on to describe the relation between flow and form, analysing how the two are part of larger cognitive ecologies of becoming. The main relevance of the article, which is fundamental to the thesis, is the explanation of how the Cartesian separation of mind, form and matter is replaced by a dialectical process-based relation of subjective intentionality and material affordance, analysed through pottery-making and discussed as an event that is in constant evolution as opposed to a discrete and isolated condition.

[60] Government of Saskatchewan, 2016. *Portable windbreak fences*. [online] Available at: <http://www.saskatchewan.ca/business/agriculture-natural-resources-and-industry/agribusiness-farmers-and-ranchers/livestock/cattle-poultry-and-other-livestock/cattle/portable-windbreak-fences> [Accessed 29 December 2016].

This Canadian local government webpage provides information regarding the deployment of wind fences in rural and agricultural areas. Initially it gives information about the general features of windbreaks, followed by the advantages and disadvantages of their use at sites that are exposed to high wind velocities, the general design parameters that they should adhere to, the degree of porosity that needs to be maintained to avoid turbulence at the immediate area behind them, and lastly the design requirements when these take the form of vertical walls. Peculiar as a reference like this may seem, it nevertheless provides very useful information, design guidelines and basic porosity criteria that have been incorporated in Design Study 06 i.e. in the design of the graded copper and aluminium element.

[61] Grant, I. H., 2011. The chemical paradigm (interview). In: R. Negarestani, ed. 2011. *Collapse: Philosophical Research and Development, Volume VII*. Falmouth: Urbanomic, pp. 39-82.

In this interview, Grant discusses the significance of chemistry as a synthetic example for a philosophical thought that goes beyond analysis and critique. This is made through an inquiry into the nature of chemistry on a universal, cosmological level as well as on its capacity to generate a new culinary paradigm. The text goes on to explain the value of chemistry as a continuous condition within which the element itself becomes secondary in comparison to the processes of dynamism, synthesis and experimentation. The ideas and discussion within the interview are useful in providing a philosophical framework for the understanding of matter as process that relates directly to the point of the thesis against the designing with matter as an inert building element. Although being detached from any design and architecture discussion the text is nevertheless very useful in defining the idea of a material continuum.

[62] Gürsoy, B., 2016. Why is making important for the culture of design? In: The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), *Living Systems and Micro-Utopias: Towards Continuous Designing*. Melbourne, Australia, 30 March - 02 April 2016. Hong Kong: CAADRIA.

This article looks into the dominant approaches to the design process and compares these to a bottom-up approach where priority is given to material engagement. The Aristotelian principle of hylomorphism is questioned initially, together with the traditional separation of mind and world that has resulted in the disconnection of form, design and material reality. The response to this is to think of design as a process ontology, and through material engagement theory argue for a dialectic emergence of form. This is discussed through a number of design examples that range from material samples to a house, which, however, are analysed rather superficially and serve more like illustrations of the author's ideas. The article is highly relevant to the research and provides a wealth or references that will be used in the design thesis.

[63] Henriques, B., Miranda, G., Gasik, M., Souza, J., Martinelli, AE., Silva, F. and Nascimento, RM, 2013. Functionally graded materials applied to dental restorative systems- a bioinspired approach. In: COBEM, *22nd International Congress of Mechanical Engineering*. Ribeirão Preto, Brazil 3-7 November 2013. [online] Available at: http://cobem2013.com.br/cd/PDF/2276.pdf [Accessed 23 May 2014].

This article consists of the authors' research into metal-ceramic functionally graded materials for use in restorations in dentistry. Remarkably similar to the enthesis region in muscle and bone, the DE junction in the boundary between dentin and enamel in teeth, allows for the gradient bridging between these two parts that otherwise have different material properties. Aspiring to attain a similar effect through a manufactured material, the authors present extensive research on the fabrication of metal-porcelain FGM with varying gradient transitions that are effectively tested for their mechanical and structural strength. The article has not been used in the thesis directly, but was nevertheless a useful source when investigating wider research initiatives in FGM in material science and beyond.

[64] Hitchcock, H.-R. and Johnson, P., 1997. *The international style*. New York; London: W.W. Norton.

The book consists of an analysis of the main traits of the International Style, followed by extensive illustrations of modernist and International Style buildings and descriptions of their main architectural features and stylistic shortcomings. Of particular relevance to the thesis is the architecture-as-volume principle according to which structure and envelope have become separate entities in the new style, moving away from the load-bearing external masonry walls of the past. Together with building component standardization, this will be used as a historical reference in the cladding sub-chapter of the thesis. Additionally, the parts discussing the capacity of personal architectural ingenuity to expand the limits of the International Style will be used as a reference in the main thesis chapter where the notion of internal form imposition on the external world is criticized.

[65] Hofmann, D. C., Roberts, S., Otis, R., Kolodziejska, J., Dillon, R. P., Suh, J., Shapiro, A. A., Liu, Z. and Borgonia, J. P., 2014. Developing gradient metal alloys through radial deposition additive manufacturing. *Scientific Reports*, 4 (5357), pp.1-8.

In this article, Hofmann et al. describe the fabrication of alloys with graded material compositions using laser deposition additive manufacturing. Following a brief introduction of commonly used 3D printing techniques for graded parts, the authors describe the fabrication of a test sample consisting of titanium, aluminium and vanadium in varying gradient consistencies. The manufacturing of a radially graded rod sample consisting of stainless steel and invar is also described. The article concludes with an analysis of a potential aerospace application of the graded rod piece, which is very useful for illustrating the benefits of the use of multi-materials at the relevant chapter of the thesis. In addition, although consisting of scientific terminology at certain parts, the article is nevertheless helpful in placing the thesis within a wider emerging context of multi-material research.

[66] Hutchins, E., 2005. Material anchors for conceptual blends. *Journal of Pragmatics*, 37(10), pp.1555-1577.

In this article, Hutchins discusses his theoretical extension to conceptual blending (initially formulated by Fauconnier and Turner), which has been termed materially anchored blending. The author starts off by explaining how his take on the theory abides to the fundamental principles of composition, completion and elaboration and then goes on to discuss a few examples of material anchoring, ranging from ones that involve physical objects the least to ones where they are utilised the most. Of particular relevance is the discussion about whether materials are represented mentally or perceived directly, while the theory itself is fundamental to the description of the "b-rep-anchored notional material blending process" in the thesis.

[67] Independent RealFlow Forum, 2011. *Different materials ID's for single realflow mesh*. [online] Available at: <http://www.realflowforum.com/viewtopic.php?f=19&t=7602> [Accessed 04 May 2017]

This online forum consists of discussions between users of RealFlow and other related software, on technical and procedural issues arising when designing in these platforms. This specific discussion concerns the mixing of liquids in RealFlow, or more particularly how a blending effect can be attained and how Maya can eventually be utilised to generate renders of the result. This is a problem remarkably similar to the one encountered in the design workflow in the research. Although this has been effectively resolved in the design, this reference has been used in subchapter 5.1.2. of the thesis, as evidence of the instability and system crashes caused by blind data editing in Maya.

[68] Ingold, T., 2009. The textility of making. *Cambridge Journal of Economics 2010*, 34(1), pp.91-102.

The argument presented in the article is against the hylomorphic model in art and technology, and for an understanding of the forms of things emerging within fields of forces and materials. The author starts off by discussing what the hylomorphic model is, followed by a description of the idea of forms as emerging from the interaction of the flows of materials and the designer. He then goes on to discuss the notion of improvisation as opposed to abduction, and of itineration as opposed to iteration. This is directly relevant to the research and more specifically in the main thesis chapter, where the argument against the top down conception of the design process and of the designed multi-material as a finished artefact is presented.

[69] Ingold, T., 2013. Of blocks and knots. *The Architectural Review*, 234(1400), pp.26-27.

In this article Ingold argues for the substitution of the block as the main fundamental element by the knot as the main constituent of 'everything'. The article starts off by discussing the fact that the building block in science and architecture is a 19th century creation and then describes Semper's writings of the time, that placed the knot and weaving as the primary building element. He then goes on to discuss the etymological origin of the word knot and the example of the carpenter who although is understood to work with parts, is presented here as performing an operation of weaving. The significant relevance of the article is its argument against the concept of being (represent by the block) and for the one of becoming (represented by the line, knot and weave). This has been used in the materialist theory literature review.

[70] Ingold, T., 2013. *Making: anthropology, archaeology, art and architecture*. London: Routledge.

In this book Ingold formulates an extensive critique of the hylomorphic model and wider tradition in anthropology, architecture and adjacent disciplines. The author starts off by providing an overview of the established theoretical models in anthropology and explains how the following will attempt to rethink these. He then briefly analyses the theory of hylomorphism and goes on to discuss a series of examples ranging from a hand axe to a house to a watchmaker through which he demonstrates the shift from an object-oriented approach to one of perceiving everything in a state of flow and becoming. The book is relevant to the thesis in a multitude of ways that mainly have to do with the usefulness of the history of the hylomorphic model presented through architectural examples from Alberti's and other medieval builders' and architects' writings, as well as of the larger theoretical position of materiality as being in constant flux.

[71] Ingold, T., 2015. *The life of lines*. New York: Routledge.

In this book, Ingold presents his theory of becoming as an ever-evolving process, which opposes the condition of being as a fixed and static entity. This argument is structured and analysed through a series of examples that have to do with the existence of physical or immaterial lines. Consisting of a wealth of material that is directly relevant to the research, the main parts that have been used in the thesis are, the discussion concerning the way that things are joined up, which can be a relation of either interiority or articulation, the critique of hylomorphism, and the brief analysis of Gibson's theory of affordances. These have been used in various parts of the thesis, namely in the introduction and in the 'Thinking with Blends' chapter.

[72] Iwamoto, L., 2009. *Digital fabrications: architectural and material techniques*. New York: Princeton Architectural Press.

Different CAD related techniques of fabrication are initially organized in thematic entities of contouring, tessellating, folding, sectioning and forming. Each of the categories is then examined through a series of installation or built scale examples. Parts such as the one about forming contain several projects that make use of composite materials like fiberglass over milled foam, resin matrix with fibre cloth and plaster with elastic fabric among others. The relevance of the book relates to its abbreviated analysis of continuous construction techniques that can relate to the practical part of the research about seamlessness.

[73] Kahn, C., 2001. *Pythagoras and the Pythagoreans: a brief history*. Indianapolis, Ind.: Hackett; Lancaster: Gazelle.

The book consists of a condensed summary of the work and philosophy of Pythagoras and how this influenced subsequent philosophical thought until the present day. The author starts off by providing an overview of the Pythagorean cultural and philosophical system as well as how this was reflected in quotidian practices. He then moves on to discuss its influence on Plato, Archytas, Hellenistic Period, Roman, Neo-Pythagorean, and medieval scientists and philosophers. This was useful in acquiring an initial understanding of the concept of duality in philosophical discourse, which is something that in the case of the thesis relates to the duality between mind and matter. According to the Pythagorean doctrine dualism is related to the indefinite, which, however, becomes definite when the number one (representing finitude) is added to it. Although rather abstract a notion, this can be used in the introduction where an overview of the theoretical discourse on duality is provided.

[74] Katavolos, W., 1960. Organics. In: U. Conrads, ed. 1971. *Programs and manifestoes on 20th-century architecture*. Cambridge, Mass.: MIT Press, pp.163-164.

In this brief article, Katavolos argues for a new type of architecture based on chemically induced growth, as opposed to a conventional top down design endeavour. The vision that he is putting forward is based on new material inventions at the time (1960s), which involved liquid substances that can expand in size and volume and rigidify once a catalyst is added to them. This led the author to write in the article of elements such as furniture and walls that can vary, expand, and be responsive to occupation and the user. The relevance of the article is the idea put forward of architecture made directly of materials, however, its limited extent and visionary style mean that it can only be used as a general reference.

[75] Kazmierczak, K., 2010. Review of curtain walls, focusing on design problems and solutions. In: NIBS (National Institute of Building Sciences), *BEST2: A New Design Paradigm for Energy Efficient Buildings*. Portland, Oregon 12-14 April 2010. Portland: NIBS.

In this conference paper Kazmierczak explains the classification, challenges and reasons for failure in curtain wall systems. He begins by outlining why curtain walls are used in buildings, points out their different classification characteristics, analyses the loads and differential movements developed between the envelope and structure of a building and describes the functions that a facade system ought to perform. The article concludes with the typical performance failures observed in curtain walling and the reasons for these that include misunderstandings of the importance of continuity in the facade layer detailing and joining between adjacent panels, poor onsite supervision of installation, coordination oversights in project delivery processes and lack of adequate knowledge about facade design. A large part of these causes is similar in nature to the ones analysed by Layzell (1997). The article is very useful in making a point about the redundancies inherent in the way that building envelopes are design and built currently and the value of a more continuous design paradigm. It will also be used in arguing for the idea of continuity at the part of the thesis that defines the concept.

[76] Kirkegaard, P.H., Hougaard, M. and Stærdahl, J.W., 2008. On computational fluid dynamics tools in architectural design, *DCE Technical Report No. 5*. Aalborg: Aalborg University.

In this article Kirkegaard et al. compare two computational fluid dynamic software, one being from the engineering field (ANSYS) and the other used in the movie and advertising industry (Realflow), in terms of their adherence to the behaviour of real flows. The comparative analysis is done with two case studies: the simulation of flow around an aerofoil and the simulation of wind flow around the Utzon Centre building in Aalborg, Denmark. Their research uses the patterns generated by ANSYS that is a scientific data driven program and therefore matching a real situation more closely, as a reference to evaluate the resemblance of the Realflow results to it. The value of the article is relating to the practice based part of the research, where Realflow is used to simulate real liquid material behaviour. The main limitation of the article is the lack of design-oriented iterative studies that would enable the refining of the resulting Realflow simulations to resemble the result from ANSYS. Although relatively small in extent, the article provides the beginning of very useful insight and a basis for analysing the validity of the material simulations in the research.

[77] Kirsh, D., 2009. Projection, problem space and anchoring. In: Cognitive Science Society, *31st annual meeting of the cognitive science society 2009 (CogSci 2009)*. Netherlands, Amsterdam, 29 July- 1 August 2009. Austin: Cognitive Science Society.

A very useful article in which the practice of thinking through things, as relating indirectly to conceptual blending theory is discussed. Initially, the principle of mental projection that resembles augmented reality is analysed, followed by an explanation of the differences between perception, projection, and imagination. The author then discusses a number of cognitive experiments in which the subjects "externalise their mental projections" as a way of increasing their cognitive capacity. This kind of mentally augmenting reality is going to be used as a reference in the part of thesis where the b-rep-anchored notional material blend is discussed. Additionally, the example of the fulcrum and weight provided before the conclusion will be used in order to illustrate what running or mentally simulating a conceptual blend is, while parts of the article will be used in explaining the reason for implementing the blending theory in the thesis in the first place.

[78] Knaack, U., 2010. *Rapids: layered fabrication technologies for facades and building construction*. Rotterdam: 010 Publishers.

A thorough analysis of rapid prototyping techniques and materials currently available is succeeded by a series of design detailing and rapid construction technology ideas. These are separated in projects relating to architecture, building construction detailing, building construction elements and facade systems and consist of either existing or speculative proposals that relate to potential future developments in the field of rapid prototyping. There is a direct link to the subject of seamlessness as the technologies analysed in the book are all intrinsically related to continuous construction methodologies the use of which can bypass or achieve an integration of contemporary building component assembly methods.

[79] Knippers, J. and Speck, T., 2012. Design and construction principles in nature and architecture. *Bioinspiration & Biomimetics*, Volume 7, Number 1, pp. 015002.

In this article Knippers and Speck investigate the role that biology and biomimetics can play in architecture. Following a description of the differences between material and structural strategies in nature and in building construction, the authors go on to extrapolate the main design principles found in nature eventually attempting to demonstrate how some of these have been applied in the design of a facade system. Their research focuses on assessing the transferability of biomimetic knowledge into architecture. The article is useful to the research topic as it provides useful information about hierarchy and differentiation across different scales in material build-ups in nature. Although not directly relevant to the idea of continuity, the article will provide very useful technical knowledge about material structuring, information about process sequences in biomimetics that the thesis will attempt to deviate from and lastly an overview that can be referenced into the thesis about the research and use of material gradients currently in architecture.

[80] Knoppers, G.E., Gunnink, J.W., van den Hout, J. and van Wliet, W.P., 2005. The reality of functionally graded material products. In: D.T. Pham, ed. 2005. *Intelligent production machines and systems: first I*PROMS virtual conference*, 4-15 July 2005. Amsterdam: Elsevier, pp.467-474.

This article is the only one (together with a research paper published in 2006 by the same authors and of the article Variable Property Rapid Prototyping by Oxman) of a very few (precisely three in total) that provide a concise overview and literature review of the software that can allow for the attribution of graded information in the computer. It starts off with a brief overview of the current state of rapid prototyping and of multi-material printing capabilities and then goes on to discuss briefly what are functionally graded materials, and what software can describe materially graded structures computationally. The authors then provide an analytical description of their custom CAD tool, termed INNERSPACETM that has been created to enable users to assign graded materiality on solid geometries. The article has been of vital importance and usefulness in the literature review of the thesis, where the available CAD software for designing multi-materially are discussed, and to a lesser extent in providing background information on the historical origins of the use functionally graded materials.

[81] Knoppers, G.E., Gunnink, J.W., van den Hout, J. and van Wliet, W.P., 2006. The design of graded material objects. In: Loughborough University, *1st international conference on rapid manufacturing*. Loughborough, UK, 5-6 July 2006. Loughborough: Wolfson School of Mechanical and Manufacturing Engineering Rapid Manufacturing Research Group.

This conference paper is almost identical in its structure and content (some parts have been rephrased and slightly extended) to the article published in 2005 by the same authors, titled The Reality of Functionally Graded Material Products.

[82] Kwinter, S., 2010. Concrete: dead or alive? In: M. Bell and C. Buckley, eds. 2010. *Solid states: concrete in transition*. New York: Princeton Architectural; Enfield: Publishers Group UK.

This article by Kwinter is part of a book dedicated to the use of concrete in architecture. It starts off by mentioning the properties of concrete as a material in-between static and dynamic phases, and then goes on to discuss the unique properties of bone as a non-isotropic material. This leads to a brief mention of Ito's Taichung Metropolitan Opera and Reiser+ Umemoto's O-14 office building in Dubai, which according to the author are the two most important buildings of the present era that use principles from bone arrangement to achieve component-less structures that are built as continuous concrete entities. These are of particular relevance to the thesis as they can be used as (very rare) references of built structures that partially avoid tectonic construction. Additionally, the example of Edison's concrete pianos who encountered the problem of making the material flow in every part of its corresponding mould and the conclusion discussing Simondon's writings against hylomorphism, of how notions of form and material can be replaced by energies, agency and information are the most useful parts of the article.

[83] Ladd, C., So, J. H., Muth, J. and Dickey, M. D., 2013. 3D printing of free standing liquid metal microstructures. *Adv. Mater*, 2013, DOI: 10.1002/adma.201301400.

The article describes methods of direct 3D writing of liquid metal on a micro scale. Through a brief mention of existing technology used to create metal microstructures such as electrical wires, the authors present four different approaches to fabricate these microstructures. The article focuses on describing the physical and metal properties of the metal used for these processes, as well as the manner that it should be deposited in order to generate continuous structures. This is useful to the research topic as it demonstrates that there already is the technology being developed to 3D print metal albeit in a small scale, that can relate to the digital material simulations. It can be claimed that since this technology is beginning to develop, it is essential to simulate the material behaviour in advance of the actual 3D printing process.

[84] LaMonica, M., 2013. Additive manufacturing: GE, the world's largest manufacturer, is on the verge of using 3D printing to make jet parts. *MIT Technology Review*, May/ June 2013, pp. 58-59.

This brief online article consists of a description of the use of 3D printing in the aviation industry. Addressed to a wider non-specialised audience, it starts off by outlining what additive manufacturing is, then goes on to discuss its use by General Electric (GE) in generating jet engine parts and the multitude of advantages that this will have in terms of sustainability and cost savings. Of particular relevance to the research is the concluding part of the article that mentions that GE are turning into the use of alloys and material mixtures as the next phase that will follow the inauguration of additive manufacturing in the industry. The deployment of various sub-materials within a larger material will be targeted to meet different functional demands. This will be used as an example of the outlook of multi-material use in industries adjacent to architecture and to make a point about the validity of the claim for its future widespread use.

[85] Layzell, J., 1997. Failure mode and effects analysis in the cladding industry. In: ICBEST'97: *2nd ICBEST conference on building envelope systems & technology*. Bath, UK 15-17 April 1997. Bath: CWCT Publications.

Described in the paper is a planning tool for identifying, analysing and effectively reducing potential risks and failures of cladding in general and of four main cladding components (sealants, gaskets, glass and metal finishes) in specific. The author initially outlines the cladding supply chain structures, as well as the reasons for cladding component failures and then goes on to analyse the Failure Mode and Effects Analysis (FMEA) tool for eliminating these failings. Of particular relevance to the thesis is the laying out of the main reasons for failure that involve oversights and flaws by installers, fabricators, supervisors and contractors among others. These will form vital evidence for pointing out the value of the design research in terms of rethinking the interface condition between cladding and structure through the use of functionally graded materials. A limitation of the article is that it precedes the development of Building Information Modelling software that would reduce the margin for error further.

[86] Leach, N., 2009. The limits of urban simulation: an interview with Manuel DeLanda. *Digital Cities AD: Architectural Design*, 79 (4), pp.50-55.

DeLanda in this article discusses the application of digital simulation tools to predict urban growth patterns. The article discusses the various forms of simulation that exist and which can be broadly split into continuous and discrete. It then goes on to analyse the structure of cities and buildings that are based on multi-agent interactions, with the cities and building themselves read as fields of processes rather than aestheticized forms. These agent systems can be used to represent a range of attributes from individual human movement to the behaviour of larger organizational structures. The relevance to the research topic is the mention of continuity in a digital environment as still being 'discretized' over a grid of a given resolution, with the control of the spatial and temporal intervals of this resulting in the appearance of continuity. This is something that can relate to the theoretical analysis of the CFD tools used in the practical part of the research. A limitation of the article is that there is not a specific design application or methodology set out that answers the theoretical aspect of the discussion.

[87] Li, A., Thornton, A., Deuser, B., Watts, J., Leu, M., Hilmas, G. and Landers, R. G., 2012. Freeze-form extrusion fabrication of functionally graded material composites using zirconium carbide and tungsten. In: Laboratory for Freeform Fabrication (LFF) at the University of Texas at Austin, *Proceedings of the twenty third annual international solid freeform fabrication symposium – an additive manufacturing conference*. Austin, USA 6-8 August 2012. Austin: University of Texas.

Li et al. discuss the fabrication process of a functionally graded material consisting of tungsten and zirconium carbide. Initially describing the available manufacturing methods for FGM, the authors analyse the freeze-form extrusion technique and then make comparisons in terms of material densities and flexural strength of a series of FGM test bars to corresponding ones made using the isostatic pressing technique. The authors conclude that isostatic pressing achieves better results than freeze-form extrusion and indicate that an improved mixing method is required to enhance the performance of materials made by freeze-forming. The article is useful for illustrating the advantages of FGM from a technical and mechanical property perspective, as well as for potentially indicating that there is a methodological link between the liquid simulation studies and the fact that FGM can be manufactured in liquid form.

[88] Liepe, L., 2013. The multi-materiality of St. George and the dragon. In: U. Albrecht and A. Mänd, eds. 2013. *Art, cult and patronage: die visuelle kultur im ostseeraum zur zeit bernt notkes*. Kiel: Ludwig, pp.199-207.

In this article Liepe discussed the theatrical qualities generated by the use of multiple materials in the statue of St. George and the Dragon in the Church of St. Nicholas, Stockholm. In the beginning of the article Liepe makes a thorough and detailed description of the positioning and type of the different materials that make up the composition of the statue. She then describes a number of examples of the arrangement of pilgrims and artefacts in religious space and suggests that the sculpture's detailed material representation of reality, as well as its central positioning contribute to the inviting of the pious to study it closely and from varying angles, which is something that augments its function as an instrument of devotion.

The article is useful for the research topic as an analysis of multi-materiality from a cultural perspective, while the part describing the 'fusion of dimensions of reality' will be used at the section of the thesis that describes the philosophical and theoretical merging that also occurs through the multi-material paradigm.

[89] Liu, Y., Birman, V., Chen, C., Thomopoulos, S. and Genin, G. M., 2011. Mechanisms of bimaterial attachment at the interface of tendon to bone. *Journal of Engineering Materials and Technology*, 133(1), pp.1-22.

The paper discusses the authors' modelling and analysis of the four distinct strategies used in the enthesis for effective load transfer. These namely consist of the shallow attachment angle of the interface tissue, the interdigitation of the transitional tissue with bone and the shaping, formal characteristics and functional grading of the connection. The intent of these analyses is to inform surgical procedures for attaching tendon to bone and to allow for a better integration between the two post-operatively. Especially relevant and useful to the research are the illustrative examples in the appendix of the paper, which describe in a diagrammatic manner the different connection strategies. These are going to be directly incorporated as geometrical and formal guiding principles in the design of the cladding to structure connection using functionally graded materials. A difficulty that the article poses is the scientific terminology used in specific parts that describe the findings of the research.

[90] Longo, G., 2009. Critique of computational reason in the natural sciences. In: E. Gelenbe and J-P. Kahane, eds. 2009. *Fundamental concepts in computer science*. London: Imperial College Press.

This article discusses the structural and procedural differences between the way that a computer generates information and how natural phenomena and processes work. The text starts off with an analysis of language and reasoning, which can be typically decomposed into the simplest possible elements and then reconstructed in order to produce meaning. This is juxtaposed with the fact that certain processes in nature have equivalent and constituent complexity as opposed to simplicity, as well as certain unpredictable variability. The latter then becomes according to the author a problem of how 'real' randomness cannot exist in the computer, the fact that minor occurring processes that have chaotic effects cannot be simulated accurately and lastly that the discrete topology of digital data is fundamentally different to the continuous mathematics of physical principles. This effective differentiation between computational imitation and 'physico-mathematical' modelling will feed into the thesis chapter on the epistemology of the material simulation.

[91] Lynn, G., 2010. *Composites, surfaces, and software: high performance architecture*. New Haven, Conn.: Yale School of Architecture.

The book consists of three distinct parts that do not directly relate to one another, but that in broad terms are concerned with the overall theme of computation and digital and material science in contemporary design through material, graphic, architectural and built paradigms. In the first part about composites, Lynn frames via examples from the boat building industry that there is a radical shift that will be occurring in material and construction technology in architecture. His main argument is that the use of composites signifies a move from clad structures that are mechanically joined together towards chemical bonds between materials that effectively abolish the idea of tectonics, which is of direct relevance to the research topic on integration. The limitations of the section about composites mainly relate to its size, as there is hardly any space given in order to expand into the subject by illustrating potential applications in architecture. This is only attempted via student project paradigms which are only shown as summaries. Parts of the book, however, are valuable in order to highlight the relevance and timeliness of the research.

[92] Lynn, G., 2011. Chemical architecture. *Log 23*, Fall 2011, pp.27-29.

In this article, Greg Lynn discusses the new shift in architecture towards the use of composite materials, and the implications that this will have on a new architectural aesthetic. He begins the article by mentioning the current shift from "assemblage to fusion" and the increasing relevance of the term plasticity that is directly related to the use of composites in architecture, goes on to mention two buildings by OMA (the Seattle public library and the CCTV tower in Beijing) that exhibit this new composite sensibility both structurally, as well as aesthetically

and then provides a brief mention of the various composite materials used both in the automotive and aerospace industry, as well as in architecture. Concluding that the cultural implications of this new type of assembly are something that will increasingly occupy architectural theory in the future, parts of the article are very useful as references for illustrating the point that the practice of fusion will form the new methodological and constructional principle in architecture.

[93] Mahamood, R. M., Akinlabi, E. T., Shukla, M. and Pityana, S., 2012. Functionally graded material: an overview. In: WCE, *Proceedings of the world congress on engineering 2012*. London, UK, 4-6 July 2012. Hong Kong: Newswood Limited.

Although part of the proceedings of an engineering conference held in London in 2012, the paper is an informative outline of the processing techniques, areas of application and future research in functionally graded materials(FGM) avoiding the use of technical or scientific terminology. In addition, the focus is on the cost implications of current FGM manufacturing methods and conclusions on which of these can be the most cost-effective if developed and researched into further in the future. The paper is useful in providing a valid background on the literature and applicability of FGM currently, while of additional applicability in the research is the explanation of the processes in which the materials are manufactured in their liquid form, which is something that can validate the use of fluid simulations for the designs. A limitation is that the analysis of the techniques does not go into depth in order to provide further background information on the energy and costs implicated.

[94] Mahboob, H., Sajjadi, S. A. and Zebarjad, S. M., 2008. Synthesis of Al-Al2O3 Nano-composite by mechanical alloying and evaluation of the effect of ball milling time on the microstructure and mechanical properties. In: The Faculty of Engineering, International Islamic University Malaysia (IIUM), *ICMN08 2008: International conference on mems & nanotechnology 2008 (ICMN08)*. Kuala Lumpur, Malaysia 13-15 May 2008.

Discussed in the conference paper is the production of an aluminium-alumina alloy and the effect that different milling times have on the alloy's microstructure and mechanical properties. At the start of the description of the conducted tests, the authors set out the target of achieving an even dispersion of alumina particles within the aluminium matrix as this is something that improves the mechanical properties of the composite. The different tests at 0, 4, 8 and 12 hours milling time are then described and the resulting samples are analysed for particle distribution at scales of 2 and 10 micrometres. The article concludes with the remark that increased ball-milling times allow for alloy samples that are stronger and of increased strength. The text is helpful for the design exercise of fusing glass with aluminium with an intervening alumina layer to hold the two together and to illustrate that the merging of alumina with aluminium does take place on a physical level in material science research.

[95] Malafouris, L., 2008. At the potter's wheel: an argument for material agency. In: C. Knappett and L. Malafouris, eds. 2008. *Material agency: towards a non-anthropocentric approach*. New York; London: Springer. Ch.2.

In this chapter of the book that discusses material agency, Malafouris critiques the typical attribution of agency solely to humans and explains how this should be perceived as a distributed condition concerning humans, as well as materials that engage with one another dialectically. The author starts off by proposing that one should begin by analysing the temporal aspects of a making act (or its chrono-architecture), then goes on to explain that what is considered to be a conscious act is preceded by the unconscious so-called readiness potential, which proves that (human) intentionality is something that should be disengaged from agency. He then describes the difference between 'prior intention' and 'intention-in-action' arguing for the latter, analyses the significance of the 'Background' as the framework that enables agency to be formed and concludes that materials afford a certain engagement with them, as much as humans have a specific objective of forming them in what is termed as a 'symmetrical' relation.

[96] Malafouris, L., 2013. *How things shape the mind: a theory of material engagement*. Cambridge, Massachusetts: MIT Press.

The book puts forward the Extended Mind Hypothesis and analyses its corresponding Material Engagement Theory (MET). Looking into a series of archaeological artefacts, as well as practices such as pottery making, the author uses MET to illustrate how the Cartesian duality between mind and body as separate ontologies is rethought as the extended mind, where things, making and mind operate within a reciprocal ecology of engagement by defining one another mutually. The book is seminal to the research as the conceptual integration or blending theory proposed within will be applied directly to the main thesis proposition according to which the designed mould and material simulation form a reciprocally engaged entity. This will be made by demonstrating that there is no one-directional sequencing in the design methodology proposed, but rather information from the material realm informing the design of form and form simultaneously (partially) constraining the formation of matter.

[97] Malafouris, L., 2014. Creative thinging: The feeling of and for clay. *Pragmatics & Cognition*, 22(1), pp.140-158.

In this journal article Malafouris explains how thinking is a process made through things and applies Material Engagement Theory (MET) in describing the act of pottery making. He starts off by explaining the “metaplastic” qualities of humans, and explaining what MET is about followed by an analysis of creating thinging as an ontological continuity between mind and matter. He then goes on to criticise the computational or representationalist view where the mind stores representations of the external world, which are then projected back into it in order to impose form over matter, and proposes instead that thinking is more often than not an unconscious activity made through making and through things. The obvious significance of this to the thesis is that it can be used to argue about the inseparability of form-making, material simulation and materiality itself in the proposed hybrid-control design method.

[98] Mensvoort, K. V., 2011. *Next nature: nature changes along with us*. Barcelona: Actar.

This compendium of a series of journal issues that have been collated in the form of a book, consists of extensive analyses of the idea of nature and how this has evolved to be an altogether different concept in a contemporary context. Also put forward is the argument that what is considered as technology, has now become another type of nature, sometimes equally unpredictable and difficult to restrict. Of particular interest and relevance to the research are the various novel material technologies incorporated in the book that are hybrids of nature and technology and effectively blur the traditional boundaries between the two. The book has provided general background information about contemporary material technologies.

[99] Michalatos, P. and Payne, A.O., 2013. Working with multi-scale material distributions. In: ACADIA, *33rd annual conference of the association for computer aided design in architecture*. Cambridge, Canada 24-26 October 2013. Cambridge: ACADIA.

In this paper Michalatos and Payne describe their proposal for a novel digital interface that allows designers to work with multi-material distributions that move away from conventional B-rep techniques. The authors use the structure of bone as a reference in which material is configured hierarchically on scales ranging from the nano to the macro and suggest that with the advent of more advanced manufacturing technologies digital tools similarly need to enable multi-material design on varying scales. Their proposed tool uses voxel representations of objects in which materials can be assigned in a gradient manner as halftone patterns. The topic of the paper is very useful for the research as it makes a similar point that the imminent multi-material printing technologies require a shift in the way design is conducted. It is also useful for the literature review part of the thesis. The limitation of the article is that it is focused around the description of the digital tool itself reducing that way the space given for extensive design examples analysis.

[100] Michalatos, P., 2016. Design signals: the role of software architecture and paradigms in design thinking and practice. *Digital Property: Open-Source Architecture Architectural Design*, Volume 86, Issue 5, pp. 108-115.

The article provides an analysis of the current shift taking place in CAD software from an objected-oriented modelling approach to one where information is modulated in scales ranging from the micro- all the way to the macro. This analysis starts off by discussing the ontological status of the current CAD tools and how the structure of this affects output form and more importantly design thinking and then goes to discuss how this model is currently being re-evaluated due to two main reasons, one being the communicative character of current software, and the other the assimilation of voxel-based representation models from the biomedical industry. The article will be used in the CAD literature review where the prevalent modes of multi-material design are discussed. A segment that is also relevant is the one where the way that b-rep CAD tools affect the way designers think in terms of componentry is mentioned.

[101] Miodownik, M., 2014. *Stuff matters: the strange stories of the marvellous materials that shape our man-made world*. London: Penguin.

The book gives a general overview of contemporary materials, how some of them came about historically and also what are their properties and uses. It starts off with a photograph taken by the author on a rooftop in London and uses this to identify all materials pictured, effectively dedicating a chapter to analyse each one. Although addressed to a wider audience and seemingly more tangential to the research, the book gives quite invaluable explanations about the structure of fused materials and alloys, which can provide background information for the explanation and definition of what multi-materiality is in the thesis. In addition, the discussion of the different material scales that exist from the atomic to the human, will be used to define the scope of the design explorations, while the passage about the animate materiality that is anticipated in the near future will potentially be used in the concluding chapter of the thesis.

[102] MIT Technology Review, 2013. *10 breakthrough technologies 2013*. [online] Available at: https://www.technologyreview.com/lists/technologies/2013/ [Accessed 02 January 2017].

This is the annual review that MIT publishes, regarding the most advanced and promising technologies that are believed to have the largest impact. In 2013, the review consisted of smart watches, ultra-efficient solar energy, memory implants, prenatal DNA sequencing, deep learning, additive manufacturing, big data from cheap phones, temporary social media, supergrids, and a robot. The relevance of the article is in terms of the additive manufacturing technology that is concerning the use of this in fabricating airplane and jet components by the company General Electric. This has been used in the introduction of the thesis as evidence towards a shift to continuous automotive and aerospace parts, as opposed to mechanically assembled pieces.

[103] MIT Technology Review, 2014. *10 breakthrough technologies 2014*. [online] Available at: https://www.technologyreview.com/lists/technologies/2014/ [Accessed 02 January 2017].

The MIT annual review consisted in 2014 of drones used in agriculture, ultra-private smartphones, the mapping of the brain, neuromorphic chips, genome editing, microscale 3D printing, mobile collaboration, the Oculus rift, robots that are agile, and smart wind and sun power. Of particular relevance is microscale 3D printing that is conducted by the Lewis Research Group at Harvard University and essentially concerns multi-material printing on a microscopic level. This technology has allowed the researchers to customise qualities such as electrical conductivity and mechanical strength within one material volume, by mixing together sub-material with different properties in a targeted manner. This has been used in the thesis introduction to make a point about the use of multi-materiality in scientific fields that are adjacent to architecture.

[104] MIT Technology Review, 2015. *10 breakthrough technologies 2015*. [online] Available at: https://www.technologyreview.com/lists/technologies/2015/ [Accessed 02 January 2017].

The 2015 version of the MIT review consisted of the augmented reality technology Magic Leap, Nano-scale material lattices, car-to-car communication, project Loon by Google, liquid biopsy, desalination on a megascale, Apple Pay, brain organoids, supercharged photosynthesis, and the internet of DNA. Of specific use here is the discussion about material lattices, which are effectively materials that have been intervened with or built from scratch at a Nano level with the main aim being to have their properties altered and customised in order to meet

specific objectives. Together with Magic Leap, project Loon, liquid biopsy, brain organoids, photosynthesis and DNA internet technologies, these were used to illustrate the fact that there was a material problem present in most the inventions and that material level innovation is encompassing an ever-expanding range of contemporary technologies. Additionally, the Nano-lattices were used as an example of the progressively decreasing scale of material intervention observed from the 2013 Technology Review.

[105] Morgan, J., 2013. *Amaze project aims to take 3D printing 'into metal age'*. [online] Available at: < http://www.bbc.co.uk/news/science-environment-24528306> [Accessed 02 January 2017].

This brief online article discusses the European Space Agency's project termed AMAZE (Additive Manufacturing Aiming Towards Zero Waste & Efficient Production of High-Tech Metal Products), a research initiative regarding the use of 3D printed metallic components in space. It starts off by describing the benefits that additive manufacturing can have on parts for satellites and cars among others, then outlines the design and fabrication method followed to construct these components and concludes by a presentation of the quantitative benefits that this technology has had when applied in the manufacturing of the nacelle hinges of an Airbus A320. This has been used as a evidence in the introduction of the thesis, where the shift from tectonics to fusion is discussed.

[106] Miyamoto, Y., Kaysser, W.A., Rabin, B.H., Kawasaki, A. and Ford, R.G. eds., 1999. *Functionally graded materials: design, processing and applications (Materials Technology Series)*. Boston, [Mass.]; London: Kluwer Academic Publishers.

This book consists of a series of articles and contributions by material scientists that have written about topics ranging from the theory and design of functionally graded materials to their manufacturing techniques and applications. This was supported by the FGM forum in Japan that promoted the dissemination of these materials outside the country. Similarly to the publication by Shiota and Miyamoto, the book consists to its largest extent of scientific terminology that makes most of it inaccessible. Very useful, however, is the introduction that provides a very interesting, in-depth and extensive analysis of the historical origins of FGM, their types, characteristics, microstructures and examples of their use. The diagrams in the introduction illustrating the structure of an FGM have been used as the main criteria dictating the success or not of the material simulation mixes

[107] Oosterman, A. and Cormier, B. eds., 2013. *Volume #35: everything under control*. Amsterdam: Stichting Archis.

This issue of Volume Magazine consists of a range of articles, all discussing the new biosynthetic approach and convergence of systems in science and beyond. Overall the topics range from the use of 3D printing in the construction industry to NBIC convergence and the invention of new material technologies like self-healing concrete and bioengineered animals that produce optimised fibre materials. Although there is no part that covers or mentions the use of functionally graded materials, the magazine is nevertheless useful as a general reference and source in innovations and developments taking place in the field of materials science, and design.

[108] OPUS (Publication Server of the University of Stuttgart), 2015. *A new connection technique for unidirectional fibre reinforced plastics with glass and carbon fibres*. [online] Available at: < http://dx.doi.org/10.18419/opus-623> [Accessed 28 December 2016].

This webpage contains information about the doctoral thesis by Jürgen Denonville on connecting a glass and metal part using fibre reinforcement. This information consists of the issue date of the dissertation, an abstract, as well as a link for downloading the thesis, which, however, is only available in German. This work was done at the Institute for Lightweight Structures and Conceptual Design at the University of Stuttgart and together with other research initiatives undertaken at the Institute has been used in the literature review of the thesis where other work done in the field of multi-materials or graded components is discussed. Here, the work concerns a composite material approach, however, the relevance relates to the fact that it investigates the connection of the same materials as in the thesis.

[109] Oxman, N., 2010. Structuring materiality: design fabrication of heterogeneous materials. *Architectural Design, Special Issue: The New Structuralism: Design, Engineering and Architectural Technologies*, Volume 80 (4), pp.78-85.

This article consists of a brief overview of themes relating to the main research areas that the author is investigating, namely natural solutions to problems of material distribution and structural efficiency, as well as the use of these to inform variable property design projects. In effect, the text starts off by briefly presenting the advantages of 'design' principles in nature i.e. an equal weight on form, structure, and materiality, followed by the author's own projects. This has been used in the literature review of the thesis, where the approaches to multi-material design by other researchers is discussed. The criticism in effect is that all computational techniques presented therein are voxel-based (i.e. not quite considering physical material properties), while a limitation of the article is that it does not provide a self-reflecting critique concerning the projects proposed and the shortcomings that these have in regard to natural creations.

[110] Oxman, N., 2011. Variable property rapid prototyping. *Virtual and Physical Prototyping*, Vol. 6, No. 1, March 2011, pp.3-31.

The paper presents the author's technique of 3D printing multiple property materials (as opposed to the conventional singular material output) and the ensuing custom software termed variable property modelling that enables designers to generate variable property parts in the computer. Presented are the current problems with "virtual and physical prototyping", the author's biomimetically-driven computer modelling technique, a literature review of available CAD for incorporating graded material information in the computer, a presentation of what functionally graded materials are, a series of variable property designs by the author, and what seems to be the beginnings of an apparatus for 3D printing multi-materials. The main use of the article has been due to its literature review, which is remarkably similar (almost identical) to the one of Knoppers, et al. (2005; 2006), as well as the use of voxel based methods in the multi-material designs proposed.

[111] Oxman, N., 2011. Finite element synthesis. In: P.J. Bártolo, ed. 2011. *Innovative Developments in Virtual and Physical Prototyping: Proceedings of the 5th International Conference on Advanced Research and Rapid Prototyping*, Leiria, Portugal, 28 September - 1 October, 2011. Boca Raton, Fla.: CRC, pp. 719-724.

The paper explores the idea of rethinking Finite Elements Analysis (FEA) as a tool for designing and generating physical prototypes with variable material properties. Oxman initially describes the way FEA is used for evaluating structural performance and as a form-finding tool, lacking however the possibility of material property editing by the designer. The author goes on to propose a theoretical model of the use of the FEA algorithm as a design synthesis tool rather than one of mere analysis, incorporated early in the design process and aimed towards the fabrication of variable property products and materially efficient building parts. A limitation of the article is that it lacks practical examples of what a Finite Element Synthesis design interface can consist of and how it can be used by the designer. It is nevertheless useful for the part of the research that discusses how a forthcoming use of functionally graded materials can have design methodology related implications.

[112] Oxman, N., Keating, S. and Tsai, E., 2011. Functionally graded rapid prototyping. In: P.J. Bártolo, ed. 2011. *Innovative Developments in Virtual and Physical Prototyping: Proceedings of the 5th International Conference on Advanced Research and Rapid Prototyping*, Leiria, Portugal, 28 September - 1 October, 2011. Boca Raton, Fla.: CRC, pp. 483-490.

In this conference paper Oxman et al. discuss their novel three-dimensional printing technique for fabricating functionally gradient materials. Initially delineating the problem of existing fabrication methods being capable of producing solely homogeneous materials, they go on to explain their objective of using precedents from nature in order to inform material distribution in the fabrication of variable-density cement foams, as well as of polymers with variable elasticity. They conclude that their method can optimize the structural and functional performance of materials, as well as conserve material usage and improve product life spans. The limitation of the paper is that the research does not go beyond the scale of the individual material com-

ponent or of the object and into suggesting potential architectural and spatial applications. It is nevertheless useful in providing references for the material description part of the thesis, as well as the validity and relevance of researching into functionally graded materials.

[113] Oxman, N., 2012. Programming matter. *Architectural Design, Material Computation: Higher Integration in Morphogenetic Design*, Volume 82, Issue 2, pp. 88-95.

This article consists of the author's research at the MIT Media Lab concerning the design of graded material parts and building components. It presents the idea of heterogeneity through different principles, such as anisotropy and graded materiality and then describes the author's techniques of graded material modelling and fabrication, as well as variable density and elasticity manufacturing. Apart from the article's obvious relevance due to its focus on heterogeneous materials, a point that is important and has been used in the literature review is the fact that the designs presented incorporate variable property principles, but these are concerning a single material changing its properties, as opposed to multi-material mixtures.

[114] Oxman, N., 2012. Towards a material ecology. In: ACADIA 12: Synthetic Digital Ecologies, *Proceedings of the 32nd annual conference of the association for computer aided design in architecture*. San Francisco, USA 18-21 October, 2012. San Francisco: ACADIA.

In this short keynote essay that is part of the ACADIA 2012 proceedings, Oxman outlines her concept of Material Ecology as a design practice that deals with matter, fabrication and environment. Described initially is the separation of material from form that following a tradition of craft started to evolve as a trend in the Renaissance, through the Industrial Revolution and Modernism and into contemporary digital design. It is then argued that at the same time, through advancements in material science and fabrication a new interest and design culture is starting to evolve towards material based design. The essay is useful for the critique in the thesis, of the CAD tools available to incorporate materiality computationally and namely the part that mentions the voxel and maxel as the digital material units through which material based design can be practised. A limitation is its short extent.

[115] Oxman, N., 2012. Material computation. In: Disseny Hub Barcelona, ed. 2012. *FABVOLUTION*. Barcelona: Barcelona City Council. pp. 256-265.

In this short article, Oxman argues for a different computational approach to design that incorporates form- and material-finding capabilities in the digital design and fabrication process. It starts off by looking into nature as a source of materially-driven form generation processes, then goes on to discuss the problem with current CAD software that is geometry-biased, and eventually describes the proposed CAD approach that incorporates material parameters and variable materiality from the start of the design process. The beginning of the article contains the statement that materiality should precede form, to which the thesis is counter-proposing an equal participation of form and materiality. The article has been used as a reference in the design literature review.

[116] Oxman, N., Dikovsky, D., Belocon, B. and Carter, W. C., 2014. Gemini: Engaging experiential and feature scales through multimaterial digital design and hybrid additive-subtractive fabrication. *3D Printing and Additive Manufacturing*, 1 (3), pp. 108-114.

The paper describes the design process for a chaise longue consisting of a CNC milled wooden chassis and a multi-material internal lining. The authors initially state their design intent for enabling a simulation-free environment within the 3D interior of the chair and then describe the use of Stratasys' Connex technology to 3D print 44 different materials that allow for variations in opacity, rigidity and colour as a result of geometrical, acoustical and structural constraints. Their research focuses on devising a computational process that assigns material gradients according to pressure distributions of the reclining human body, as well as the optimal structural support for it. The article is useful for the literature review section of the thesis and for the argument that a multi-material design process of this kind although assimilating multiple functions and design objectives, does not at the same time take into account the individual material properties that the resulting multi-material consists of.

[117] Pawlyn, M., 2011. *Biomimicry in architecture*. London: RIBA Publishing.

A synopsis of speculative and applied design principles and techniques found in nature. There is a range of scales covered from material to structural to environmental to urban waste control and disposal, with recurring themes relating to sustainable management and performance. The different examples from nature come from either individual organisms or from large ecosystems and are rather superficially examined. In quantitative terms, there is a relatively wide range of construction and material methods found in nature that can form a basis for further in-depth practical analysis.

[118] Picon, A., 2010. *Digital culture in architecture: an introduction for the design professions*. Basel: Birkhäuser.

This book attempts to give an overview of the impact that a turn towards the digital will have on architecture and the wider design profession. The author starts off with a historical overview discussing the relation of architecture and digital information in the past, then goes on to mention and analyse a series of pre-digital era architectural projects, and concludes by discussing the impact of the new digital technologies on design practice. The book is not central to the research per se, but has been useful as a more general read that helps to historically situate some of the digital design practices that are discussed in the thesis.

[119] Poulsgaard, K. and Malafouris, L., 2016. Models, mathematics and materials in digital architecture – creative imagination at the human-computer interface. In: S. Cowley and F. Vallée-Tourangeau, eds. 2017. *Cognition Beyond the Brain*. Cham: Springer International Publishing. pp. 283-304.

The authors use Material Engagement Theory (MET) to examine creative thinking and cognitive processes in relation to digital design in architecture. They start off by discussing what MET is, following this up with an analysis of the work of Bézier and Mark Burry in the Sagrada Familia. They then discuss what conceptual integration theory is and how the various design processes for parts of the Sagrada Familia can be analysed under that prism. These are of obvious and direct relevance to the thesis and will be used in the main chapter, where the application of conceptual blending and materially anchored blends in the proposed design methodology are discussed. Of additional importance is the description of the work of David Kirsh, part of whose writings have been used to illustrate the aforementioned mental blending procedure.

[120] Ratto, M., 2011. Critical making: conceptual and material studies in technology and social life. *The Information Society: An International Journal*, 27(4), pp. 252-260.

Described in the article is the practice of critical making, as a way to extend critical reflection of technology through material engagement. Ratto starts off by analysing the problem of disconnection between the theoretical understanding of technological objects and the physical interaction with them. He then outlines different pedagogical models of learning through making, describes a material prototyping event organised at the RCA in which first ideas of critical making were tested and then goes on to describe the main part of the article, named the Flower Power Walled Garden. The latter was a design exercise of making cellular automata modules that would interact with one another and with participants eventually reflecting on this interaction. The article was part of the reading list for participation at the CAADRIA conference and although related to materials it is not directly relevant to the research per se.

[121] Rawlings, R. D., 2002. Materials science and engineering. In: Unesco, 2002. *Knowledge for sustainable development: An insight into the Encyclopedia of life support systems, v. 1*. Paris; London: UNESCO/EOLSS, pp. 1038-1040.

The pages about functionally graded materials in the chapter on materials science and engineering, outline the advantages, types and indicative applications of FGM. Initially mentioning the fact that almost all interfaces in nature are graded, the author describes the failings of conventional joints and coatings at interface points in composites and analyses the three categories of interface, surface and bulk FGM. Although not expanded upon extensively, these are going to be relevant for the section of the thesis where graded connections in nature are discussed, for the chapter on FGM that describes the different classification methods that exist for these materials, as well as for demonstrating the potential advantages of utilizing FGM in architecture.

[122] ReaFlow 2014 Documentation, 2014. *HyFLIP - Viscosity Values*. [online] Available at: < http://support.nextlimit.com/display/rf2014docs/HyFLIP+-+Viscosity+Values> [Accessed 29 December 2016].

This webpage contains information about the viscosity values of different liquid substances at different degrees centigrade. Published online by Next Limit Technologies, the company that has created RealFlow, the page contains a brief explanation about the SI unit used for inputting dynamic viscosity values in the program, which in this case is Pascal Second. This has been useful in obtaining the values that have been input in Design Study 03, concerning the dynamic viscosity of water and oil at twenty degrees, as well as in the main design of the curtain wall interface, where the one of glass in its molten state was input in the simulation.

[123] RealFlow 2015 Documentation, 2015. *Nodes - Particle Meshes*. [online] Available at: < http://support.nextlimit.com/display/rf2015docs/Nodes+-+Particle+Meshes> [Accessed 29 December 2016].

This basic webpage is part of the online documentation for RealFlow and contains information about what a mesh is and how it can be used within the software. It provides a very brief and basic explanation about the different types of settings that can be used in meshing particles in the program and then describes in an equally basic manner the difference between a single mesh and a mesh sequence that is applied over the whole time span of the simulation. The usefulness of this page is in its use as a reference in the starting part of the design studies, where there is a basic description of what a particle mesh is.

[124] Riegl, A., 1928. The modern cult of the monument: its character and its origin. In: V. Schwartz and J. Przyblyski, eds. 2004. *The nineteenth-century visual culture reader*. New York: Routledge. Ch.8.

This seminal text by Riegl discussed by Küchler in the concluding chapter of the Social Life of Materials: Studies in Materials and Society book, is one of the first observations of a shift in the appreciation of new as opposed to old materials, which took place in art and architecture in the beginning of the 20th century. The chapter is divided in parts, that discuss age, historical, deliberate commemorative and lastly newness value in the context of the appreciation of monuments. It will be used in the introduction of the thesis to situate the research in a historical lineage of material innovation, the traces of which go back as far back as the early 20th century.

[125] Richards, D. and Amos, M., 2014. Designing with gradients: bio-inspired computation for digital fabrication. In: ACADIA 14: Design Agency, *Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture*. Los Angeles, USA 23-25 October 2014. Los Angeles: ACADIA/ Riverside Architectural Press.

This article consists of the analysis and description of a generative modelling technique by the authors that is voxel-based and allows for structural topology optimization and also for multi-material distribution on a designed volume. The authors initially provide some background on existing research that relates to their work, describe their novel technique and present three case studies of its application, concluding with a description of possibilities for further development. The article is directly relevant to the research, as it involves a 3D physics simulation as part of the modelling procedure, while a part of it deals with an exploration of multi-material assignments on one of the designed pieces. This is limited, however, to a small section and is presented mainly to suggest further development possibilities of the CPNN-NEAT modelling method of the authors. It will be used in the literature review section of the thesis.

[126] Ritter, A., c. 2007. *Smart materials in architecture, interior architecture and design*. Basel; Boston: Birkhäuser.

A catalogue of a range of materials used in architecture that have the capabilities to exchange energy and matter, or the capacity to alter their shapes and volumes in response to a stimulus or to generate forms of energy. The extensive analysis of these is by initially identifying their composition and properties and then outlining the products made by them and the architectural projects that they have been used in. In addition, the scope of the analysis is to examine how cost-effective the use of the various smart materials is, what environmental benefits they might have and what is the potential for a future improvement of cost and functionality. The book is useful in providing a technical background to the research and also situating the type of materials used in the designs against a substantiated table of contemporary smart materials. The limitations of the book are that the practical uses of materials as well as their analysis to a high extent are examined through their conventional applications into facades, walls etc. and not described for their possibilities to allow for the rethinking of these types.

[127] Ritter, G. ed., 2015. *Between action and the unknown: the art of Kazuo Shiraga and Sadamasa Motonaga*. Dallas: Dallas Museum of Art.

The book accompanied an exhibition of the work of the two artists and consists of texts about their life, association with the Gutai art movement, as well as paintings and installations. This is useful in providing in-depth information about Gutai, Shiraga's performative art installation Challenging Mud and Motonaga's Water Works pieces. The first is going to be used in order to situate the work of the two artists in the wider context of postwar Japan and discuss how this relates to Shiraga's attempts to bring forward the individuality of the subject by focusing on the human body in his art. His act of immersing in mud in Challenging Mud will be used in the part of the thesis where the idea of a full virtual immersion for designing the blending container is discussed. The Water Works installations in their turn are useful in discussing the relation of containing material and contained substance, which is a central theme in the research.

[128] Safran, Y. ed., 1989. *Frederick Kiesler, 1890-1965*. London: Architectural Association.

The publication was produced to accompany an exhibition of Kiesler's drawings at the Architectural Association. In its first part, it consists of descriptions of his work throughout his life and is followed by texts written by Kiesler himself, namely about functionalism and modern architecture and also a critique and description of Marcel Duchamp's Large Glass painting. Of particular relevance is the former, in which he analyses the phases of the mechanization of dwelling construction, effectively defending the intimacy of building and making, as well as the lack of a design method of the primitive man. This will potentially tie in with the claim in the thesis of the consequences of direct building that multi-materiality can enable if it becomes implemented in the immediate future. His rejection of conventional architectural design and representation tools like the plan, in search of other alternatives for designing can also potentially back up the claim for the use of material simulations as a different method.

[129] Schmidt, C. W., Knödler, P., Höppel, H. W. and Göken, M., 2011. Particle based alloying by accumulative roll bonding in the system Al-Cu. Metals, Volume1, Issue 1, pp.65–78.

This article precedes the one in which the manufacturing technique for graded aluminium sheets is present and concerns an analysis of the various changes in the properties of the material. It begins with a review of the different materials that have been used for particle reinforcement and then provides a brief description of the type of particle mixture proposed by the authors, the way this has been bonded in its surrounding metal matrix, and then a series of tests on measuring the stress-strain, electrical conductivity, and yield strength of the resulting formation. Similarly to the article published the following year by the same authors, this is useful in providing technical information for setting up the simulation study in Design 06.

[130] Schmidt, C. W., Ruppert, M., Höppel, H. W., Nachtrab, F., Dietrich, A., Hanke, R. and Göken, M., 2012. Design of graded materials by particle reinforcement during accumulative roll bonding. Advanced Engineering Materials, Volume14, Issue 11, pp.1009–1017.

In this article, Schmidt et al. present their technique of bonding copper particles that have been sprayed in a gradient manner within an aluminium sheet to increase its tensile strength. They start off by describing the roll bonding technique that involves the recursive high pressure rolling of sheets of metal, then describe the consistency of the aqueous mixture of particles that has been sprayed on the sheet, followed by a description of mathematical methods for calculating the particle content within the sheet and accurately determining the corresponding increase in tensile strength. The article is of a scientific nature but it has nevertheless been used to inform Design Study 06 in the relevant chapter of the research where the mixing of aluminium and copper is presented. An additional use will be of the photographs of the microstructure of sandwiched copper within aluminium.

[131] Scientific American, 2012. What's a voxel and what can it tell us? A primer on fMRI. [online] Available at: http://blogs.scientificamerican.com/observations/whats-a-voxel-and-what-can-it-tell-us-a-primer-on-fmri/ [Accessed 19 April 216].

This online article consists of a description of the use of voxels in medical imaging. The text starts off by analysing an fMRI scan showing brain activity, then goes on to describe how voxel-based imaging is used in the scan and how data analysis techniques are employed to detect brain activity. Towards the end of the passage, a striking remark is that voxel-based fMRI can eventually be used as a thought predicting, as well as brain-reading tool. The article is useful in providing basic information about what voxels are and how are they are used in contexts outside the architectural discourse. This will be useful in the literature review part where voxels and voxel design are explained.

[132] Searle, J., 2012. Intentionality: an essay in the philosophy of mind. Cambridge: Cambridge University Press.

This book is a philosophy of language study, namely concerning the mental phenomenon of intentionality and its association with conditions of causation, perception, action, and meaning creation. Effectively being placed in the space between perception and action, intentionality here is examined as a pre-conscious condition, on top of the different other states that it can be found in. Two of these, namely prior-intention and intention-in-action have been used as key points in the discussion about agency and the argument in the thesis that the b-rep container for the material simulations is not created as a predefined (in the mind) form, but rather that it has emerged in a much more entangled and relational manner. Searle's states of intentionality in effect were rethought through Malafouris's writings that all intentions are intentions-in-action (and not prior-intentions) in order to validate the above point of non-anthropocentric agency in the b-rep creation process.

[133] Shiota, I. and Miyamoto, Y. eds., 1997. Functionally graded materials 1996. Amsterdam; Oxford: Elsevier.

This book consists of a number of scientific research and conference papers concerning the various design, modelling and manufacturing techniques, as well as properties and applications of functionally graded materials. As the vast majority of these articles is of a scientific nature and to the most part terminology that is incomprehensible by a non-scientific audience is used, the main and most accessible part has been the introduction. This consists of concise definitions, analyses of the characteristics and an overview of the use of functionally graded materials at the time of the book's publication. The definitions provided there have been used as references in the literature review and design development parts of the thesis.

[134] Shiraga, K., 2007. Kazuo Shiraga: paintings and watercolours. London: Annely Juda Fine Art.

This book consists of Kazuo Shiraga's work for an exhibition that was held at the Annely Juda Fine Art Gallery in London. Of particular interest is the part in which the 'inner bipolarity' characterising his work is expanded upon and cross-referenced in relation to his life. Renowned for his body paintings Shiraga drew from the seemingly conflicting traditions of intellectual vs. emotional painting and was employing conscious, as well as unconscious actions to engage and paint with materials, most often than not immersing himself in mud or other media in order to do so. The book is decidedly and remarkably relevant to the hybrid-control design thesis, in which a design model of parallel top-down and bottom-up form creation is argued for. Although structured slightly differently in terms of the order and timing of its actions, Shiraga's employment of a combination of the calculated and the accidental bears a striking similarity to the proposed methodology of the creation of a measured envelope within which materials are allowed to fuse and self-structure.

[135] Silver, M., 2011. Many from one. Log 23, Fall 2011, pp.30-34.

This article was published in the same journal issue as Chemical Architecture by Lynn and is in many ways a continuation and extension of the discussion about composite material use in architecture. It begins by describing the use of composite materials in the Boeing 787 Dreamliner and in the Beechcraft Premier I aircraft, which although of a much smaller size to the former had a much more extensive and complete application of composite materials in its hull. The main point that the author then makes is that the previous model of structure and infill that has been prevalent in architecture since time immemorial is now giving way to a continuous merging of structure with skin and in effect with programme. This also means that there is no longer the need for coordination between structural frame and openings for instance, with this point forming a useful reference in the thesis when arguing for the implications that multi-material application will have on an architectural level.

[136] Simondon, G., 1989. The genesis of the individual. In: J. Crary and S. Kwinter, eds. 1992. Zone: Incorporations v.6. New York: Zone Books. pp.297–319.

In this essay, Simondon proposes a different take to substantialism and hylomorphism according to which individuation is stemming from an individual being. Instead he puts forward the idea that individuation precedes the individual in the form of potentiality that is immanent in a pre-individual state. Apart from the fact that this theory rethinks the hylomorphic model, the essay is useful for the part where the process of crystallisation is discussed. The formation of a crystal in this instance is seen as a form of resolution stemming from the pre-individual state where form, matter, and energy exist in tandem. This has been used as a reference in 3.2.6.10. where the issues of acceptable agency in the simulations is discussed.

[137] Spina, M. and Gow, M. eds., 2012. Material beyond materials, composite tectonics. Los Angeles: SCI-Arc Publications.

Book of the proceedings of a conference held in 2011 at the Southern California Institute of Architecture in Los Angeles. The event was centred on the use of composite materials in architecture and the implications that this can have on the conception, design and construction of buildings. Although not directly linked to the theme of multi-materiality, there are ideas about formal continuity, variable material properties and system convergence versus system discretization that are nevertheless still relevant to the research. In addition, directly useful is the article by Tom Wiscombe, which is the only one discussing the idea of multi-materiality, as well as the description in various articles of the redundancies in current construction processes that are a result of inadequate knowledge management and transfer between disciplines. This latter part will be used to back-up the claim of the thesis regarding the efficiencies inherent in multi-material architecture. A limitation of the book is that each of the articles does not have enough space to expand into the various themes relating to composites.

[138] Spuybroek, L., 2008. *Architecture of continuity: essays and conversations*. Rotterdam: NAi Publishers.

Here, Spuybroek argues that although architecture and buildings are composed of elements, the same does not need to be the case when analysing, discussing, and theorising about architecture. He effectively puts forward the proposition of fusing "tectonics with experience, abstraction with empathy and matter with expressivity." The book has effectively been referred to as it provides an account and concept of continuity that operates on a theoretical level, rather than the materially-based seamlessness that is the main topic of the thesis. This has been valuable as a rather remote, but at the same time very rare theoretical reference that relates loosely to the thesis.

[139] Spuybroek, L., 2011. *The sympathy of things: Ruskin and the ecology of design*. Rotterdam: V2 Publishing.

In this book Spuybroek argues for the rethinking of modernist and twentieth century understanding of aesthetics and uses the aesthetic theory of Ruskin as a way to perceive contemporary architecture. Of particular relevance is the concept of sympathy that is discussed extensively in the book. Borrowed also by Ingold in his description of things having an end-to-end articulation that is different to the sympathy of the knot or of parts connecting in their interiority, this concept has been touched upon briefly in the thesis introduction. This was namely at the part where the etymological origin of the word tectonics is discussed, and how this comes from carpentry, which for Ingold is a process of knotting that is contrary to articulating.

[140] Studart, AR., 2013. Biological and bioinspired composites with spatially tunable heterogeneous architectures. Advanced Functional Materials, Special Issue: New Materials through Bioinspiration and Nanoscience, Volume 23 (36), pp. 4423–4436. Birkhäuser.

This feature article of the Advanced Functional Materials journal analyses naturally occurring functionally graded materials that vary their mechanical properties over their volume. Following an initial analysis of the material particle structuring on nano- and micro-scales, the author goes on to describe his designs of synthetically manufactured 'bioinspired' composites. The article is useful for the part of the thesis that discusses the advantages of using paradigms from nature to inform the configurations of the different materials in the design simulations. It is also relevant in firstly proving the point that there is already research in fields adjacent to architecture about heterogeneous materials and secondly, in framing a potential future of synthetic material systems that are graded, responsive and tuned to varying external influences. The limitation of the article is that it is focused on small scale material samples rather than discussing larger scale implications of the possible uses of these new types of materials.

[141] Tamke, M., Nicholas, P., Ramsgard Thomsen, M., Jungjohann, H. and Markov, I., 2012. Graded territories: towards the design, specification, and simulation of materially graded bending-active structures. In: ACADIA, ACADIA 2012: Synthetic digital ecologies: proceedings of the 32nd annual conference of the association for computer aided design in architecture. San Francisco, USA 18-21 October 2012. New York: ACADIA.

The paper is part of the ACADIA 2012 conference proceedings and consists of the description of two active bending structure designs using glass fibre-reinforced polymer strips. The authors initially provide a historical overview of active bending form-found structures and then describe their own designs of two gridshell installations using the same technique. Of particular relevance to the thesis is the description of the assimilation and inputting of material properties into a digital environment and also the use of Finite Element simulation software to calculate deformation of material and the overall form at multiple-scales, over time and with specific properties of the material used. This will be used to illustrate the point in the thesis, of the significance of the use of material databases to be input into the simulation environment in order to directly assign material characteristics, as well as specify fusion compatibilities. The limitation of the article is a lack of clear illustrations that demonstrate some of the design principles in a graphic manner.

[142] Teknik og Viden, 2011. Functionally Graded Building Components. [online] Available at: <http://www.teknikogviden.dk/artikelarkiv/2011/9/functionally-graded-building-components-.aspx> [Accessed 3 March 2014].

This online article is a summary of the Graduated building components (Federal Institute for Research on Building, Urban Affairs and Spatial Development, 2011) research initiative and consists of a brief discussion regarding the potential use of materially graded components in buildings. It starts off by mentioning the current impact of the building industry on the environment in general and then goes on to discuss how the use of functionally graded architectural elements, such as floor slabs and columns can have significant impacts on reducing CO2 emissions. This is because targeting material distribution where it is structurally needed can reduce the otherwise unnecessary use of materials homogeneously. This will form evidence in the introduction that demonstrates the current research conducted towards graded material use in architecture and for illustrating the reason of dedicating a PhD thesis to these.

[143] Thomopoulos, S., 2011. The role of mechanobiology in the attachment of tendon to bone. IBMS BoneKEy, (2011) 8, pp. 271–285.

This journal review examines the function to structure relationship at the functionally graded attachment site between tendon and bone. Analysed further is also the use of appropriate mechanobiological techniques for achieving successful healing of the insertion site. Of particular relevance to the thesis is the section termed 'mechanisms for overcoming the mechanical mismatch between tendon and bone', in which the author describes the strategies employed in the enthesis for effectively transferring loads between muscle and bone. Namely these consist of a shallow attachment angle of tendon into the bone, the morphology and shape of the attaching tissue, the interdigitation between the connecting materials and the functional grading of the connection. These strategies are going to be informing the structuring of the materials at their point of fusion in the design of the cladding-to-structure connection. In addition, some parts of the article are going to be referenced in the chapter of the thesis describing the characteristics and relevance of the enthesis as a model that informs the design studies.

[144] Thomopoulos, S. Birman V. and Genin G. eds., 2013. Structural interfaces and attachments in biology. New York, NY: Springer.

This book is addressed to surgeons and medical practitioners and consists of an in-depth medical analysis of the structure, material composition and mechanical properties of attachments within the human body. The problem of attaching dissimilar material parts is a problem that has always occupied surgeons and has been met with varying degrees of success. This has been the case as these attachments in the human body occur in a graded fashion and are very hard to replicate and amend artificially. The book effectively discusses the challenges that are posed in doing that and how developments in bioengineering can help overcome the current limitations. Although addressed to an audience with a scientific background and in parts being incomprehensible by a non-specialised audience, the book provides in-depth information about the enthesis that will help elucidate some of its properties and characteristics that can be transferred over in the multi-material design proposed in the thesis.

[145] Thompson, R., 2007. Manufacturing processes for design professionals. London: Thames & Hudson.

This is an encyclopaedia of the various fabrication processes relevant to the design professions. The description of each one starts off with the typical applications of the specific method, the quality that can be attained in the finished parts, the design opportunities that the technique offers, the costs involved and its overall environmental impact. This is useful in obtaining information about the die casting, injection moulding, anodizing and other methods used in fabricating the different components of a cladding panel. More specifically, the costs and environmental impacts of each of these will be discussed in the cladding interfaces thesis subchapter, in order to make a point about the hazardous nature and redundancy of some of the processes involved.

[146] Tibbits, S., 2016. Self-Assembly Lab: experiments in programming matter. London: Routledge.

This book consists of the author's studies in materials that can self-configure and assemble, as well as a series of interviews with practitioners from engineering and design research. The research projects conducted at the Self-Assembly Lab at MIT essentially form the structure and backbone of the publication, and consist among others of shape-change multi-materials, 4D printed material formations, and the use of DNA as a smart ink. The obvious relevance is regarding the author's multi-material investigations that were briefly discussed in the thesis literature review. Additionally, there was a mention in the book of the material science technique of directed self-assembly, as well as of the collaboration between designer, tools, and materiality that should be the case when attempting to program matter. These were used as references in various parts of the thesis.

[147] Tomlin, M. and Meyer, J., 2011. Topology optimization of an additive layer manufactured (ALM) aerospace part. In: Altair Engineering, 7th Altair CAE technology conference. Gaydon, UK 10 May 2011. [online] Available at: http://www.pfonline.com/cdn/cms/uploadedFiles/Topology-Optimization-of-an-Additive-Layer-Manufactured-Aerospace-Part.pdf [Accessed 6 June 2014].

This research paper is concerned with the fabrication of the nacelle hinges that hold in place the operable parts of turbine casings in airplanes. The standard hinges have been manufactured up until now by welding together metal parts that were cast in shape, a process that has carried with it several material and cost-related redundancies. The proposed substitute of this procedure in this case, is to perform a topology optimisation routine of the solid metal part, remove material where it is not needed and then 3D print the component in titanium. This has had an impact on reducing the overall weight of the aircraft, as well as reducing CO_2 emissions. There are in effect many parallels to the curtain wall segment redesign, namely in the removal of material in the connection, the use of 3D printing to fabricate the continuous component, with the useful part being the evidence of the advantages of the operation.

[148] Tsamis, A., 2010. Go brown: Inner-disciplinary conjectures. EcoRedux: Design Remedies for an Ailing Planet Architectural Design, Volume 80, Issue 6, pp.80-85.

This article, discusses a voxel based approach to design in which the focus is shifted from objects to the notion of the environment and effectively to qualities and qualitative relations. The author starts off by discussing the relation of the human body to its waste and the fact that these have been typically kept separate, and then goes on to make a case for an ecological conception of the environment in which all elements are integrated as constituents in a process of resource exchanging. The relevance of this article concerns the latter part in which Tsamis's voxel-based approach to designing with properties and gradients is described. This will be used in literature review of the thesis where the voxel approach is critiqued as although the claim is for the distribution of properties and gradients, these are limited to colours and other basic parameters that are not material properties.

[149] Tsamis, A., 2012. Software Tectonics. [online] Available at: https://dspace.mit.edu/handle/1721.1/77777 [Accessed 19 December 2016].

This webpage contains the summary of the PhD thesis titled Software Tectonics by Alexandros Tsamis, one of the main researchers that are investigating computational methods of designing with multi-materials. Interestingly here, Tsamis is also proposing a graded architectural skin that does away with the tectonic assemblies found in traditional building envelopes. At the same time, the main difference of this to the present thesis is that it is concerned with the creation of a voxel-based software environment for multi-material design for its most part and the envelope discussion comes as an aftermath to this initial research. In addition, a main difference is the use of voxels as opposed to the particle system elements utilized here. The PhD abstract has been used as a reference in the literature review of the thesis.

[150] Turner, M. and Fauconnier, G., 1995. Conceptual integration and formal expression. Metaphor and Symbolic Activity, 10(3), pp.183-203.

In this article, Turner and Fauconnier, discuss their conceptual blending theory and the "many-space" conceptual model. They start off by describing briefly what a mental space is, following this up by analysing the idea of conceptual blending through a series of practical examples, and also what the main aspects of both conceptual and formal blending consist of. The article eventually finishes of with a summary of the main parts of this theory. The content is fundamental to the thesis in the part where the proposed multi-material design workflow is discussed and namely the claim that the initial creation of a containing mould for the liquid blending simulation is a materially conceived and driven task. This is discussed in the context of b-rep use, which is the result of a historic separation between design and materiality that took place in mid twentieth century, with the main claim being that although in this instance one is working with a material-less entity, one has to think of designing with it in material terms.

[151] Varenne, F., 2001. What does a computer simulation prove? The case of plant modelling at CIRAD (France). In: Society for Computer Simulation (SCS), 13th European simulation symposium. Marseilles, France 18-20 October 2001. Ghent: SCS Eur. BVBA.

The article gives an overview of the epistemology of computer simulations, their validity and the different views that exist in regard to their usefulness in science and sociology. The author starts off by providing a literature review on the credibility of simulations as expressed by scientists and philosophers, goes on to present the definitions that exist on what a simulation actually is, formulates three main theses that summarise these definitions and proceeds by giving an example of a plant growth simulation. The paper eventually concludes by making a point that a simulation forms a third means of acquiring new insights, between theory and experimentation, while making a point that sometimes it can be even better than a real experiment mainly because of the degree of accuracy that can be obtained digitally as opposed to analogue calculations. The article is going to be useful for providing an overview on the use of simulations at the part of the thesis where the material blending simulations are discussed. A limitation of the article is the poor use of English at certain points.

[152] Vincent, J. F. V., 2003. Biomimetic modelling. Philosophical Transactions of the Royal Society B- Biological Sciences, 358 (1437), pp. 1597-1603.

Vincent in this paper discusses the workflow of knowledge transfer between biology and engineering in a similar manner to the article by Fratzl (2007). This is done through analysing examples of manufactured products the design of which is based on principles found in nature and biology. The majority of these principles are observed in shells and plants, where the morphology and microstructural behaviour of their constituent cells are analysed in terms of their energy absorption and dissipation characteristics. The paper's relevance to the research topic is relating to its elucidation of the links between knowledge of material processes and its translated design outcome on one hand, and methodologically to the Finite Element Analysis procedure used in the some of the examples. The main limitation, however, is that these links are discussed from an engineering point of view with a greater emphasis on the underlying physics rather than the design resolution. Although not forming the basis of the research, the article will nevertheless be useful in providing factual information that can back up the use of principles from nature in the thesis.

[153] Velhinho, A., Botas, J.D., Ariza, E., Gomes, J.R. and Rocha, L. A., 2004. Tribocorrosion studies in centrifugally cast Al-matrix SiCp-reinforced functionally graded composites. Materials Science Forum, 455-456 (2004), pp. 871-875.

Velhinho et al. discuss the effects that corrosion has on the material structure of a silicon carbide reinforced aluminium disc. The paper briefly describes the current uses of aluminium matrix composites and following that the corrosion testing procedure and results of an aluminium silicon carbide FGM slid against a cast iron pin both under dry, as well as in water infused conditions. Their research focuses on the complicating effects of water lubrication on the wear behaviour and corrosion studies. Although not directly relevant to the research due to its technical nature, parts of the paper that discuss the applications of the aluminium composites in various industries can be used as supplementary material to illustrate a more widespread usage of FGM, discussed at the functionally graded material chapter of the thesis. In addition, the part describing the use of centrifugal casting methods for the manufacturing of the material samples can be used to validate the relevance of the fluid simulations in the design studies.

[154] Vincent, J. F. V., Bogatyreva O. A., Bogatyrev N. R., Bowyer A. and Pahl, A., 2006. Biomimetics: its practice and theory. J. R. Soc. Interface (2006) 3, pp. 471–482.

Vincent et al discuss the transfer of knowledge and principles from biology to engineering and vice versa, similar to some of the ideas discussed in the article by Vincent (2003). The authors mention a number of applications of biological principles into product design and then go on to analyse the problem-solving system TRIZ and their own invented Bio-TRIZ, as methods to render knowledge from biology more accessible to engineers and technologists. The article is very relevant to the research as it goes on to discuss what is termed by the authors sub and super-systems in nature, which are hierarchically interlinked and the analysis of which can feed into the discussion about material supersets in the thesis. The main limitation is the emphasis of the paper on a logical framework analysis that eschews to go into a more detailed analysis of its application in a more formal, well designed outcome. The discussion will be useful, however, in the research on continuity spanning between different sub and super material fields.

[155] Young, M., 2013. Digital remediation. The Cornell Journal of Architecture 9: Mathematics, 9, pp.119-134.

Here, Young discusses the changes in the way architectural geometric information is mediated that has occurred as a result of the use of digital tools. The article starts off by describing how architectural mediation has shifted from the verbal, direct tradition of conveying building information by the medieval stone masons to the conversion of this information into scaled, measurable drawings during the Renaissance. This is followed by an extensive description of how physical design practices taking place in the automotive and shipbuilding industries eventually informed the creation of CAD software that have become today's new tools of mediation. Of particular relevance to the thesis is the physical material basis of main CAD commands such as lofting and sweeping, which is something that will inform the initial discussion about b-reps and their lost material association in the conceptual blending part of the thesis.

[156] Yu, C. L., Wang, X. F., Tong, X., Jiang, H. T. and Wang, G. W., 2007. Integrated liquid-phase sintering of glass-alumina functionally graded materials. Science of Sintering, Volume 39 (Issue 2), pp.133-144.

Discussed is the sintering mechanism of a functionally graded material consisting of alumina and glass that is examined in different orders of scale ranging from half a millimetre down to two micrometres. The manufacturing method of the material using ball milling and sintering is initially mentioned, followed by an analytical explanation of the shrinkage characteristics of the material post-sintering, the morphology of the alumina powders and the bonding characteristics between the two materials. This is useful in regard to the design of the cladding panel detail using graded materials and in order to provide evidence that the bonding of glass and ceramic (alumina) is currently possible. Part of the article is to a large extent incomprehensible due to the scientific terminology used.

[157] Wang, H.-H., 2013. A case study on design with conceptual blending. *International Journal of Design Creativity and Innovation*, 2(2), pp.109-122.

This is one of the very few articles that discusses conceptual blending theory and its practical application in a design context. It starts off by discussing what conceptual blending theory and integration networks actually are, what are the constitutive principles of a conceptual blend, as well as the different types of integration networks and how these can be applied in the design of a table lamp in which Taiwanese aboriginal mythical topics become design features. A shortfall is that conceptual blending is used in this instance in a metaphorical manner, whereas the thesis argues for a direct application of the theory in fusing together design information. It is nevertheless very useful as a reference for constructing the generic and input spaces that will feed into the blend space of the multi-material curtain wall detail.

[158] Watanabe, Y., Inaguma, Y., Sato, H. and Miura-Fujiwara, E., 2009. A novel fabrication method for functionally graded materials under centrifugal force: the centrifugal mixed-powder method. *Materials*, 2009, 2, pp.2510-2525.

The authors describe their novel technique of fabricating FGM containing nanoparticles that differs from the conventional centrifugal solid-particle method. The typical processes for creating FGM are mentioned initially, the centrifugal casting method is then discussed in more detail and a description follows of the fabrication of a copper-silicon carbide and a titanium dioxide-aluminium FGM. The research focuses on the appropriate particulate size and density analysis of the materials to be mixed, as well as a hardness and imaging-based evaluation of the manufactured samples. The article is useful to the parts of the thesis discussing the relevance and semblance of the liquid material simulations to real-life FGM fabrication methods, the discussion about the extended capabilities of FGM through the aluminium and titanium dioxide material that has photo-catalytic properties and lastly for the part where the general uses and applications of FGM are discussed. The limitation of the article is that the fabrication method described only achieves the dispersion of nanoparticles on the surface of the functionally graded material.

[159] Watanabe, Y. and Sato, H., 2011. Review fabrication of functionally graded materials under a centrifugal force. In: J. Cuppoletti, ed. 2011. *Nanocomposites with unique properties and applications in medicine and industry*. [pdf] InTech. Available at: <http://www.intechopen.com/books/nanocomposites-with-unique-properties-and-applications-in-medicine-and-industry/review-fabrication-of-functionally-graded-materials-under-a-centrifugal-force> [Accessed 30 August 2014].

This chapter consists of research into the various types of gradients formed in multi-materials under different manufacturing methods. The authors start off with a useful explanation of the two main types of gradients, namely continuous and stepwise structures, and then go on to summarise the most important techniques for manufacturing FGM, which are the centrifugal, centrifugal slurry, and centrifugal pressurisation methods. They then go on to provide detailed analyses of each of the methods that consist of diagrams of the manufacturing setup, and of the centrifugal force positioning in relation to the materials to be fused, images of the various multi-material compositions under different forces, as well as graphs of the particle distributions within the FGM. This article has been one of the most useful sources discussing the fabrication of multi-materials, parts of which have been used in subchapter 3.2.6.11 in the thesis.

[160] Watari, F., Yokoyama, A., Omori, M., Hirai, T., Kondo, H., Uo, M. and Kawasaki, T., 2004. Biocompatibility of materials and development to functionally graded implant for bio-medical application. *Composites Science and Technology*, 64 (6), pp. 893-908.

This paper describes the fabrication and biocompatibility of a titanium/hydroxyapatite FGM for use in medical implants. There is an initial mention of the different types of materials (singular, bi- and functionally graded) used in implant applications, followed by a description of the mechanical, animal implantation and visual tests of the results. The research also focuses on appropriate sintering methods for the creation of the FGM, as well as on imaging techniques for analysing the formation of new bone structure around the implants. The article will provide further information for illustrating the benefits of using FGM in the respective chapter of the research. Although the scale of the various samples examined is in the region of micrometres, the aim is to nevertheless use parts of the article to point out the capability of these materials to provide continuous transitions between otherwise dissimilar conditions.

[161] Weinstock, M., 2010. *The architecture of emergence: the evolution of form in nature and civilisation*. Chichester: Wiley.

This book departs from standard form and space biased architectural discourse and provides an alternative historical analysis of civilisation based on ecological, cultural and informational development. Consisting of four parts, each discussing the four themes of nature and civilization, climate, land based development, and the emergence of living organisms, the main usefulness of the publication to the research is its analysis of the generation of form. This is discussed as emerging within the domain defined by the genetic blueprint of an organism and the environmental factors acting upon it during embryological development. Also akin to the generation of form in the thesis within the two defining parameters of material behaviour and container design, this has been used as a reference in 4.3.5., where the formation of the enthesis in the human body is discussed.

[162] White, A., 2016. Burning man: Alberto Burri and Arte Povera. *Artforum*, January 2016, pp. 206-215.

White discusses the combustible innovation works of Alberto Burri and their subsequent influence on the work of Arte Povera artist Giovanni Anselmo. The author situates Burri's work within its post war European Informel Painting context and then discusses his use of industrially produced materials to question established ideas of authorship and symbolism in art. This topic is useful to the research as Burri's work consisted of materials subjected to the effects of physical forces, with the resulting art pieces being an outcome of this subjection. The diminished role of the author in this process was to effectively set up the conditions in which the various plastics, burlap pieces and acrylic and PVA on Celotex materials will be exposed to, which as a design practice has direct parallels to the material simulation set out in the thesis.

[163] Window and Facade Magazine, 2016. Curtain Wall Systems. *Window and Facade Magazine*, 3 (2), pp.31-45.

The article consists of a concise summary of curtain wall types, how the various types perform in terms of sustainability, the standards that need to be attained in designing building envelopes, as well as the appropriate materials that can be used in different parts of a system. Of particular relevance to the research is the latter part of the article in which the various causes of failure in cladding systems are discussed. Among others, these include inadequate design and testing, incorrect installation and non-coordination of the parties involved in the process. Evidence from this latter part will be used in the cladding interfaces subchapter of the thesis, where the benefits of re-designing the curtain wall through a multi-material are discussed.

[164] Winsberg, E., 2003. Simulated experiments: methodology for a virtual world. *Philosophy of Science*, 70 (1), pp.105-125.

This paper analyses the relation between theory, simulation, and experimentation. The author starts off by mentioning other philosophical texts discussing the autonomous nature of simulations and goes on to initially argue that simulations are essentially semi-autonomous entities that straddle the domain between theory and experimentation. Of the three main types of simulations, the paper is concerned with ones that are discretised, while effectively the point made is that simulations have become experiments themselves in the sense that they are not driven by theory (as sometimes they can contradict the theory on which they are based on) nor by their fidelity to real world data (as most often than not they are used to learn about the physical world). This is very useful in discussing the limited resemblance to reality of the types of material gradients achieved through the fusion simulations in the thesis.

[165] Winsberg, E., 2009. Computer simulation and the philosophy of science. *Philosophy Compass*, 4 (5), pp. 835-845.

The main areas covered in the article are recent philosophy of science writings on simulations, as well as a description of the reasons why philosophers can gain a lot of valuable knowledge from the practice of simulations. Provided in the beginning are the three main definitions of what a simulation is, followed by an analysis of the epistemology of computer simulations, their resemblance to experiments and their implications on the understanding of the structure of theories. This is useful in providing background knowledge about the current discussion on their validity as a way to understand the behaviour of models. Of specific relevance is the part about material similarities between the processor of a computer and the simulation of the properties of a silicon device, as well as the part describing multi-scale simulations. The latter will be used to critique the limitations of the design tools used in the research. The article is addressing the philosophy of simulation only and not any design related themes.

[166] Winsberg, E., 2015. Computer simulations in science. In: E. N. Zalta, ed. 2015. *The Stanford Encyclopedia of Philosophy*. [online] Available at: http://plato.stanford.edu/entries/simulations-science/ [Accessed 05 November 2014].

This online article covers a large range of topics that relate to the epistemology behind computer simulations in an encyclopaedia type of format. Indicatively, it covers the three different definitions of what a simulation is (ranging from narrow to broad), the types of computer simulations that exist (equation, agent, multiscale and Monte Carlo), their purposes, epistemology, relation to experiment and to the structure of scientific theories, as well as their relation to fiction. There are parts of the article that are invaluable in explaining sections of the thesis that have to do with material simulations, namely with the problem of the limited capabilities of particle systems that can be addressed with the use of hybrid multiscale simulations and sub-grid modelling, as well as with the verification and validation of the attained data. The article is philosophy of science related and therefore there is no discussion about design or architecture.

[167] Wiscombe, T., 2010. *Structural ecologies*. Beijing: AADCU.

This book is a monograph that consists of the work of architecture studio Emergent. Discussed are various design projects ranging from medium sized facade systems to whole buildings, the vast majority of which is not built and speculative in nature. The main relevance of this publication to the research are the new techniques based on the convergence of building systems and multi-materiality that it is putting forward. These are mostly targeted towards a formal rethinking of tectonics through fused building system assemblies, but not getting extensively into an in-depth discussion regarding the various aspects of multi-materiality itself. At the same time this book and work of Tom Wiscombe overall have been used as a reference in the literature review as one of the few examples of research in graded materiality.

[168] Wiscombe, T., 2012. Beyond assemblies: system convergence and multi-materiality. *Bioinspiration & Biomimetics*, Volume 7, Number 1, pp. 015001.

A seminal article capturing the transition from the prevalence of design research on composite materials to the beginnings of speculating about the relevance and potential use of multi-materiality in architecture. The article starts off by providing an overview of the part-to-whole thinking in construction and the weak correlation of building trades and systems at the moment and then through a series of prototypical designs discusses the impact that the use of composites can have on architecture by eliminating these messy correlations. It then moves on to discuss the application of multi-materiality in architectural design. Of particular relevance is the latter part, which will be used to back up the claim about the envisaged shift towards multi-materiality, as well as the potential avenues it can open in architecture both functionally, as well as aesthetically.

[169] Wiscombe, T., 2014. Discreteness or towards a flat ontology of architecture. *Project*, Issue 3, Spring 2014, pp. 34-43.

In his latest article to date, Wiscombe describes his concept of architecture consisting of "supercomponents" that are relationally linked together in a non-hierarchical manner, while at the same time maintaining their individuality. A number of buildings designed by the author are used to expand further on this idea, through instances such as the relation of building mass to the ground plane, the decoupling between envelope and interiority, as well as the use of building surface "tattoos" to organize openings, provide structural support and produce formal effects. The article is useful for the section of the research that discusses the wider theoretical framework that the idea of continuity is placed in, with the relevant part being the idea of flat ontology placed in-between a discourse that favours the discreteness of the object versus one that diffuses objects into a continuous dialectic of relations (initiated by Deleuze and pursued in architecture by people like Sanford Kwinter among others). Additionally, the closing remarks of the article that mention the changes taking place in the world of construction with the advent of new technologies, will provide further material for demonstrating the relevance of the subject matter. A limitation is that although having a purely architectural focus, at the same time the design argument is derived through a non-expanded theoretical proposition, rather than an analytical take on the imminent technological and material realities.

Research Dissemination

[170] Grigoriadis, K., 2014. Material blends: particle systems as a tool for designing a continuously graded windbreak element. In: T. A. Estévez, ed. 2014. *2nd International Conference of Biodigital Architecture & Genetics*. Barcelona: Bubok Publishing S.L. pp.246-254.

[171] Grigoriadis, K., 2014. Mixed matters: the problems of designing with functionally graded materials. In: ENHSA (European Network of Heads of Schools of Architecture) and EAAE (European Association for Architectural Education), *What's the Matter? Materiality and Materialism at the Age of Computation*. Barcelona, Spain 4-6 September 2014. Barcelona: European Network of Heads of Schools of Architecture.

[172] Grigoriadis, K., 2014. Material fusion: a research into the simulated blending of materials using particle systems. In: E. M. Thompson, ed. 2014. *Fusion- Proceedings of the 32nd International Conference on Education and Research in Computer Aided Architectural Design in Europe, Volume 2*. Newcastle upon Tyne, UK: Department of Architecture and Built Environment, Northumbria University. pp.123-130.

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