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RESEARCH ARTICLE

Computational and conceptual blends: Material considerations and agency in a multi-material design workflow

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Abstract The assimilation of functionally graded (or multi-) materials into architecture is deemed to enable the rethinking of current architectural design practice and bring back material considerations at the heart of the early design process. In response, the paper outlines a functionally graded material (FGM) design workflow that departs from standard early-stage CAD, which is typically performed via computer elements devoid of materiality. It then analyses this workflow from a theoretical perspective, namely through Edwin Hutchins' materially anchored conceptual blending, Lambros Malafouris' Material Engagement Theory (MET) and John Searle's concepts of intentionality. The aim is to demonstrate that due to the superimposition of material considerations that precede and succeed the CAD operation, working with material-less entities during early-stage FGM design is not logically sustainable. Additionally, multi-materiality allows for the questioning of authorship in the design process and leads to a repositioning of agency from the subject to the locus of engagement with digital materials and their affordances.

1. Introduction

1.1. FGM

Functionally graded materials (*FGM*) or *multi-materials* consist of two or more materials fused in a graded manner in one volume, without any mechanical connections. They were invented in Japan for use in space shuttle engines (Fig. 1). Fusing materials such as carbon/carbon and silicon

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carbide with a graded silicon carbide/carbon layer in between, allowed for the creation of thermal barriers in the combustion chamber of these engines capable of withstanding surface temperatures of 1700 °C across a <10 mm cross section.

Although invented back in the nineteen-eighties, FGM are only becoming architecturally relevant today, due to the scaling up of 3D printing (which is now used to generate entire buildings) and the advancement of multi-material additive manufacturing. Research work on FGM application in architecture (Michalatos, 2016; Grigoriadis, 2016; Wiscombe, 2012; Heinz and Herrmann, 2011) shows that these materials have the potential to change established design and fabrication practices. For instance, FGM promise a fundamental shift in construction, pointing towards a future where the assembly of individual elements to make a building will be superseded by the material integration of tectonic systems. According to Tom Wiscombe (2012), "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." Of several anticipated changes, this paper will initially outline a digital design process with FGM that departs from standard CAD practice, and it will then focus and expand on the analysis of this bespoke design workflow from a theoretical perspective.

1.2. B-rep

When looking into standard computational design processes, the use of boundary representations (or B-rep) is the ubiquitous CAD method for generating form digitally. B-rep are the digital equivalent of hollow containers devoid of internal content (Fig. 2) and are used in commercial software like Rhino to describe the envelope of an object and ultimately of a space and a building. One of the reasons for this absence of material information in B-rep is that "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). Many of the primary design operations in these fields relate predominantly to issues of surface 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 dynamic behaviour of a vessel in water or air. Surface and geometric continuity therefore take precedence over materiality and content.

Additionally, another reason is the homogenization of both the "chemical composition" and "physical structure" (DeLanda, 1995) of steel and other industrial metals in the past century. This "uniformation" made the behaviour of materials predictable and "a good deal easier and more foolproof" (Gordon, 1988, p. 135) and led to the routinisation of design tasks as "there is already a great deal of accumulated experience" attached to the use of homogeneous materials. In effect, the structural behaviour of a component became a question of shape and size, and B-rep enabled exactly that; manipulation of width, length, height, volume, and other geometrical features to generate a digital design. Again here, geometry takes precedence over predictable material behaviour.

On a theoretical level, the use of B-rep with its inherent absence of materiality at early design stage means that "design remains within the domain of the mind and of the immaterial" (Gürsoy, 2016, p. 854). Additionally, "form precedes [...] matter and is conceived in advance in the mind" (ibid., 2016, p. 854), with internal representations (i.e., mental "images" of forms) being output in the external world (digital environment) through the manipulation of shape and volume of material-less computer elements (B-rep). This corresponds to the historic model of the active human exercising their agency upon the passive world and it is not different to what Vasari (1998, p. 290) wrote about half a millennium ago: "the greatest geniuses sometimes accomplish more when they work less, since they are searching for inventions in their minds, and forming those perfect ideas which their hands then express and reproduce from what they previously conceived with their intellect". More significantly, this still prevalent, deeply entrenched, hylomorphic and entirely anthropocentric idea of form imposition upon materially inert objects equates mind to the human brain. According to it, creative, cognitive processing all takes place between perception and action, with mind and the material world being ontologically separable. From an architectural point of view, this means that "the process of architectural design is (mis)construed as narrowly linear and intentional, as if thought precedes and directs a designer's actions—thus reinforcing the impression of the architectural design process as more cerebral than materially engaged" (Bardt, 2022).

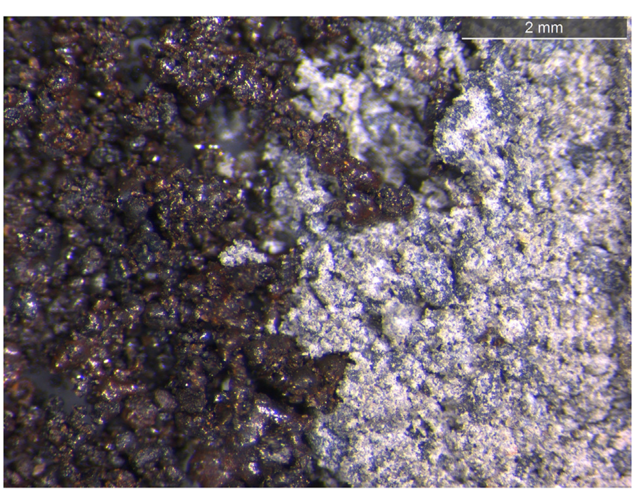

Fig. 1 Close up photograph of a functionally graded material © ESA (https://www.esa.int/gsp/ACT/projects/functionallygraded/).

1.3. Methods

In response, this paper will outline a process of designing a building envelope segment (Fig. 3) with FGM using a CAD method that departs from standard B-rep paradigm. The reason for redesigning a curtain wall with FGM is due to the multitude of problems, such as the very high embodied

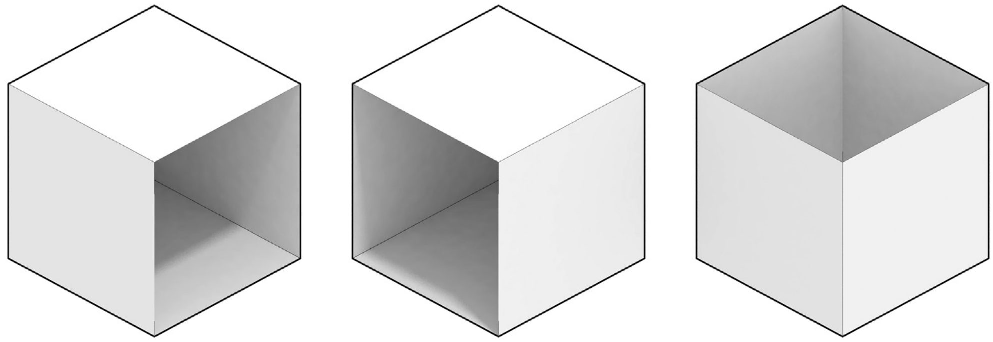

Fig. 2 Rendering of Rhino polysurfaces (B-rep) showing their hollow interior and material-less envelope.

energy and deterioration of its parts over time, that stem from its component-based make up (Window and Facade Magazine, 2016). Replacing the envelope's discrete elements with a fused and component-less material arrangement would minimise or eliminate these problems. In terms of CAD technique, fusion can typically occur with particulate or liquid materials. Therefore, the workflow presented utilises the digital equivalent of liquid mixing to generate the multi-material detail.

1.4. Research questions

Following this, the focus is on the concept of agency and the role of B-reps in the early multi-material CAD process. More specifically, various theoretical 'tools' are employed to interrogate the following questions:

- Is it possible (and logically sustainable) to design solely with B-reps and without material considerations in the first stage of a multi-material design workflow?
- Is the multi-material design resulting from this process an outcome of the author's intentionality or does the agency lie elsewhere?

These tools come from cognitive theory and the philosophy of the mind and are namely Material Engagement Theory (MET) and Conceptual Blending. The latter is elaborated on in Section 3.1.1., while MET is relevant here as it introduces a relational theory of how people inhabit the world where mind and material engagement are ontologically inseparable. This is done by collapsing the hard distinctions between internal and external cognitive processes. In effect, MET proposes that material engagement acts as a fundamental cognitive resource i.e., that we think with and through things in action.

Additionally, John Searle's concepts of intentionality are used in Section 3.2.2. to address the second of the questions above i.e., of design being a product of an intentional act. Searle proposes that communicative acts have conditions of satisfaction and a direction of fit. The latter regards the direction of intention i.e., from word-to-world, or world-to-word. In the first, words need to change to match something taking place in the world, while in the second, the world needs to change to match the words. An example of this is, "A bought two pens" and "A, please buy two pens". The first is a word-to-world fit that is only satisfied if it is true, while the second is world-to-word and is satisfied when the world is changed to match the words.

These concepts are effectively used to explain how this anticipated new way of building with FGM and a designer's early engagement with (digital) materials enable the rethinking of the aforementioned narrow linearity and

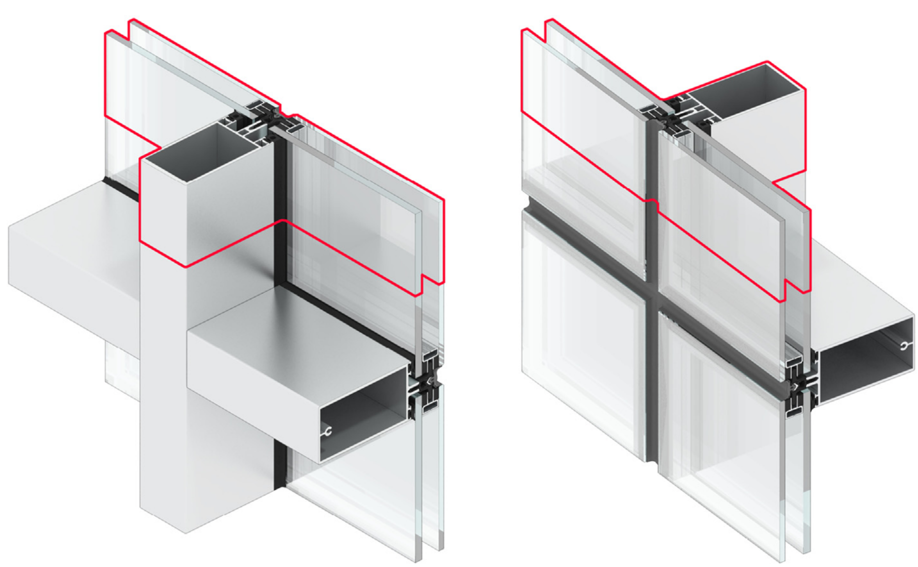

Fig. 3 Renderings of the curtain wall envelope segment with the part that is redesigned with an FGM highlighted in red.

intentionality of the architectural design process. More importantly, they demonstrate that the incorporation of (multi-) materiality in the design process, albeit in its digital form, shifts this linearity to "a richer [...] process in which ideas, designs, and meaning emerge not from a priori intent but from reflection, engagement, and recursive iterations" (Bardt, 2022).

2. Multi-material design

2.1. Voxels

Regarding potential multi-material CAD software that can describe materiality and gradients between different materials, the main accessible methods are particle system elements and voxel modelling. Voxels are mainly an analytical tool for the visualisation of scientific and medical data. Rather than being expressed by vertex coordinates (like polygons/B-reps are), voxels are the three-dimensional equivalent of pixels that are regularly spaced in a volumetric grid. Each voxel consists of single or multiple values such as opacity and colour, while the space between each voxel is reconstructed via approximation.

Although suitable for storing material information and visualising computer gradients, the main issue with voxel-based software used in architectural design, or in adjacent fields like game design is that the distribution of voxel/material values is "not based on mathematical models" (Zadick et al., 2016, p. 55). Physically, molten glass will exhibit a rheological behaviour that is determined by its intensive properties. This behaviour is different to the one of molten metal. With voxels, it is possible to define the properties of each data point, but not to assign these properties relationally across the entirety of the voxel grid to accurately simulate material behaviour. Additionally, there are voxel-based generative design approaches like topology optimisation (TO) where material distribution can be based on boundary conditions, support points and loads, but TO is typically done with a single material, with multi-material optimisation still being in its infancy.

2.2. Particle systems

The incorporation of laws of physics in particle system software on the other hand allows the modelling of rheological behaviour by controlling parameters such as viscosity, material density, surface tension and internal pressure (with some of these receiving scientific values, such as kg/m^3 for density). Additionally, two or more particle system elements with different material properties can be blended in a continuous volume consisting of areas of 100% fluid consistency and graded regions in between. This capability to input material parameters that define flow behaviour is deemed closer to reality than the limited accuracy of voxel data distribution. It is therefore used in the multi-material design presented.

When designing using a particle system (or fluid) simulation, the *form of the mould* that the particles are going to be contained or poured into is a main design parameter to be considered. As in the physical world, the mixing of fluids requires a container. Secondly, for the fluid materials to find an arrangement in space and gradients to be formed between them the *forces* or *agency* that affect the simulation also need to be attributed. Gravity for instance is the ubiquitous force acting upon any material. Thirdly, in terms of the materials themselves, the parameter that needs to be considered is the *fusion compatibility* that they exhibit, as fusion between non-chemically compatible substances can be simulated in the computer, but not fabricated physically.

2.3. Curtain wall interface design

2.3.1. Fusible materials

When it comes to the redesign of the interface of glass to its adjacent aluminium frame in a curtain wall panel, research shows that it is not possible to fuse glass with aluminium in an FGM directly. It is possible, however, to fuse aluminium with alumina (Birman and Byrd, 2007), namely in "aluminum matrix composites reinforced by nanoceramic particles" (Mahboob et al., 2008, p. 240). In addition, there exists "a method of percolating [...] molten $CaO\text{-}ZrO_2\text{-}SiO_2$ glass into [...] [a] polycrystalline sintered alumina substrate to prepare glass-alumina functionally graded materials" (Yu, et al., 2007, p. 134). It is therefore technically feasible to use alumina as an interface material in an aluminium-alumina-glass multi-material (Grigoriadis, 2015, 2018).

2.3.2. Mould form

Regarding the form of the mould, this is initially designed as a continuous enclosed volume 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. Looking at multi-material connection examples, the *enthesis* in the human body is a graded connection between the soft tissue of the muscular system and the osseous one of the skeletal system. Muscle having high tensile strength and bone being good in compression, there are several "mechanisms for overcoming the mechanical mismatch" (Thomopoulos, 2011, p. 273) between the two materials. These can be summed up as *a. multiple* attachment sites that "add to the stability of the anchorage" (Benjamin, et al., 2006, p. 479), and *b. interdigitation* i.e., the scalloping of the junction to "increase the bonding between the tissues" (Benjamin, et al., 2006, p. 479). These principles are effectively employed in the mould design and rather than having a continuous linkage between aluminium and glass, the connection is split into *multiple* points that are all inserted into the receiving volume at a *shallow angle* (Grigoriadis, 2015, 2019) (Fig. 4).

2.3.3. Agency

In terms of *agency*, the main objective is to draw this from existing manufacturing examples of multi-materials, so that there is a reciprocity between the computational setup and physical reality. Main FGM manufacturing techniques include *centrifugal powder forming* and *gravity sedimentation* among others. To assign the aluminium, alumina, glass materials, separate particle systems need to be set up for each material, on either side of the mould. This effectively results in six particle systems in total. As far the mould configuration is concerned, there are five sub compartments placed vertically within the master mould that contain the materials to be fused over the course of the simulation. As the aim is

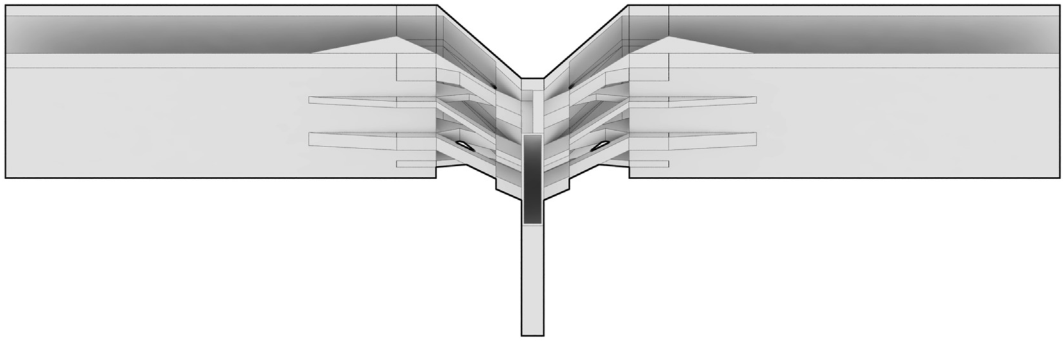

Fig. 4 Rendering of the B-rep mould for the material blending simulation.

for these to be blended crosswise across the vertical mould, a centrifugal force is deemed appropriate to achieve this. This force is the same as the one acting in the centrifugal powder forming method.

2.3.4. Simulation run

Consequently, with all the above parameters in place, the simulation is initiated with the alumina placed in the central part and molten glass on either end of the container, and aluminium in the central part. The blending in this case reaches the required formation after approximately 10 s and is eventually terminated at twelve (Figs. 5 and 6). The criteria to stop the simulation at 12 s are visual and they have to do with the arrangement of the two materials at their point of fusion being the same as in an FGM. The characteristics of this arrangement will be expanded upon in Section 3.1.7.

3. Theoretical analysis of the multi-material design process

3.1. The question of materiality in early design process

With the design workflow summarised, the following will address the first research question i.e., *is it possible (and logically sustainable) to design solely with B-reps and without material considerations in this first stage of the multi-material design workflow?*

The response is that in the proposed methodology form generation and manipulation does not take place in an isolated manner but through superimposing material considerations on the B-rep. Additionally, when designing with B-rep one must consider the particularities of the material simulation that ensues. As it is explained in the following, these superimpositions are made through a process akin to Edwin Hutchins' (2005) *materially anchored conceptual blending*.

3.1.1. Materially anchored conceptual blending (MACB)

"What essentially happens in those cases [(materially anchored blends)], 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) (Fig. 7). Hutchins describes this process through the example of the mental formation of a line of people queuing up to purchase theatre tickets. 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 is not a queue. For it to become "a queue, one must project conceptual structure onto the line. [This] structure is the notion of sequential order" (Hutchins, 2005, p. 1559) and it is termed the *trajector* i.e., a notional vector superimposed on the line of people. "Phenomenologically, the object that emerges from the blending process, that is the queue, is experienced in

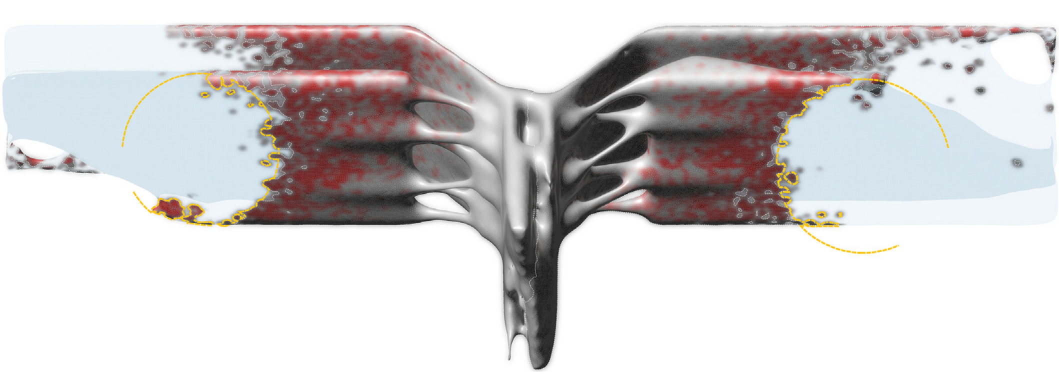

Fig. 5 Internal view of the redesigned multi-material detail. Blue represents glass, red is for alumina and the grey regions are aluminium.

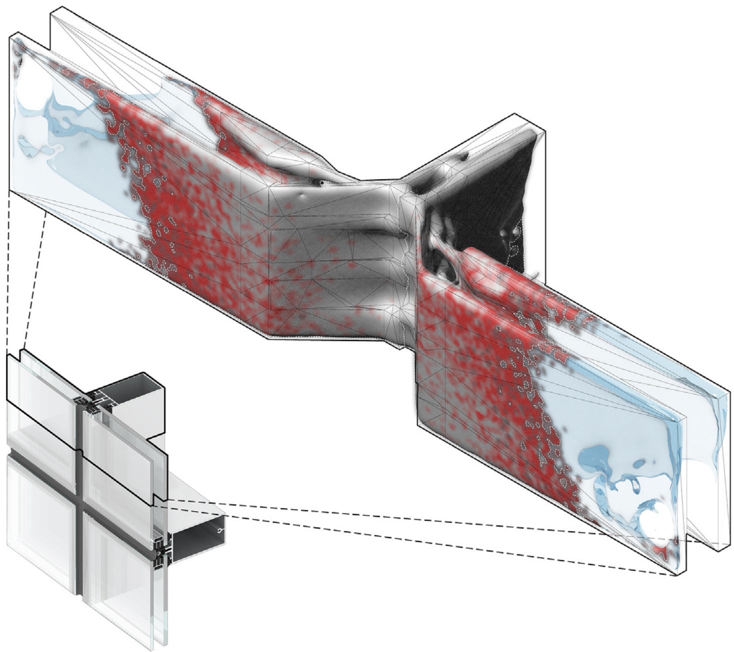

Fig. 6 Axonometric rendering of the multi-material detail, showing its relation to the original curtain wall segment.

the perception of the material structure" (Hutchins, 2005, p. 1559) (Fig. 8). Additionally:

> "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)

3.1.2. MACB in the FGM design process

The question is then how materially anchored blend theory can be applied to the design of the multi-material curtain wall detail. As mentioned, the manipulation of material-less B-reps is the main way of designing in commercial CAD software. Part of the FGM workflow is the creation of digital containers for materials to be mixed into and unavoidably one must resort to B-rep manipulation to achieve that. However, although one is working with these material-less entities, one is in fact projecting material structure on them. In the queue example, Hutchins was proposing that to complete the blend "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). The B-rep in this case makes sense in the wider context of it being used as a mixing vessel within which material fusion will occur eventually.

Additionally, the materials that are mixed are three, ordered from the one that is structural (aluminium) in the

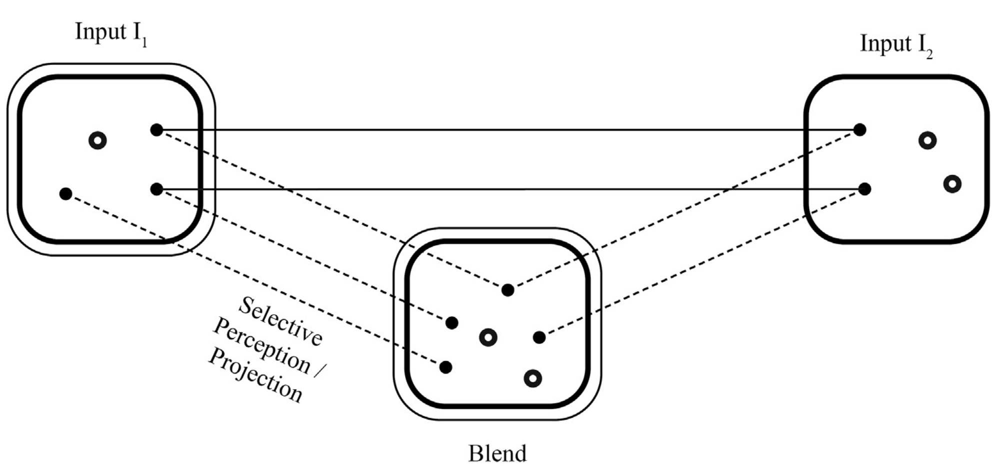

Fig. 7 Diagram of a conceptual blend with a material anchor, showing the two input spaces and emergent blended space.

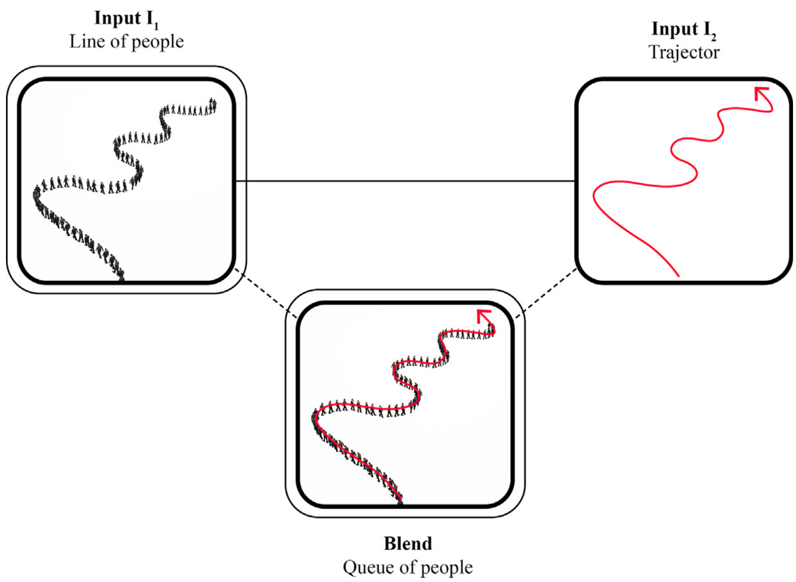

Fig. 8 Diagram of Hutchins' example of the trajector blended with a line of people to conceive the formation of a queue.

centre, to alumina on either side of that and glass at the two ends of the B-rep container. This necessitates the creation of compartments that contain these individual sub-materials. Effectively, there needs to be sequential ordering of them from the centre to either side, in a similar manner to the queue of people. This means that when one is looking at the B-rep one must firstly think in broader material terms, secondly in terms of sub-materials/sub-compartments and thirdly in terms of directionality of the sub-material arrangement.

3.1.3. B-rep anchor

Going into the structure of this mental process more specifically, there are two mental input spaces of "conceptual elements and relations" i.e., one of digital materials (to be placed within the B-rep) and the other of the trajector (to give sequential ordering to the sub-materials), and a third input space of a "structured configuration of material elements" (Hutchins, 2005, p. 1561) i.e., of the B-rep itself. "As is the case with all blends, cross-space mappings between conceptual and material elements link the two spaces and selective projection from the inputs into the blended space give rise to emergent properties" (ibid., 1562). Here, the two emergent properties are the sequential organisation of the sub-materials in the B-rep that will hold the sub-materials, as well as the "stabilization of the representation of these conceptual relations" through the B-rep. Effectively, "a mental space is blended with a material structure that is sufficiently immutable to hold the conceptual relationships fixed while other operations are performed" (ibid., 1562). The B-rep in this case is worked upon, and design operations performed, while it holds the above mentioned digital sub-materials relations fixed. In effect, instead of a material anchor it forms a *B-rep anchor.*

Testing this hypothesis against the conditions that signify a material anchor, "[material] elements are 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]" (ibid., 1562).

3.1.4. B-rep anchored conceptual material blend

In simple terms one is looking at a B-rep and projecting material information on it. In a more elaborate understanding of this process, the virtually material-less but directly engaged with and as a result 'real' (but non-material) B-rep, forms an anchor onto which materials which are not physical but are perceived as real are projected, to give emergence to a perceptually blended space in which one is working with a material-less entity but thinking and designing it, with materials in mind. Previously, the result of the blend was simply the formation of a queue mentally. In this case what Hutchins termed a materially anchored conceptual blend becomes a *B-rep anchored conceptual material blend* (Fig. 9).

3.1.5. Materiality in the early design process — summary

Summarising, the container for blending computational materials is designed using conventional CAD elements that initially appear to be immaterial. By a process of conceptual completion, however, this operation is seen in relation to the material simulation that follows, as well as the material references that precede the design. The process of designing the container is based on a B-rep forming an anchor onto which material and sequential ordering information is projected. This goes against the idea of mentally generated form that is conventionally developed in a CAD environment, with materiality only being a consideration at later design stage when it is too late for it to contribute to anything formally.

3.2. The question of agency

The aim in what follows is to address the second research question of *whether the resulting design is an outcome of*

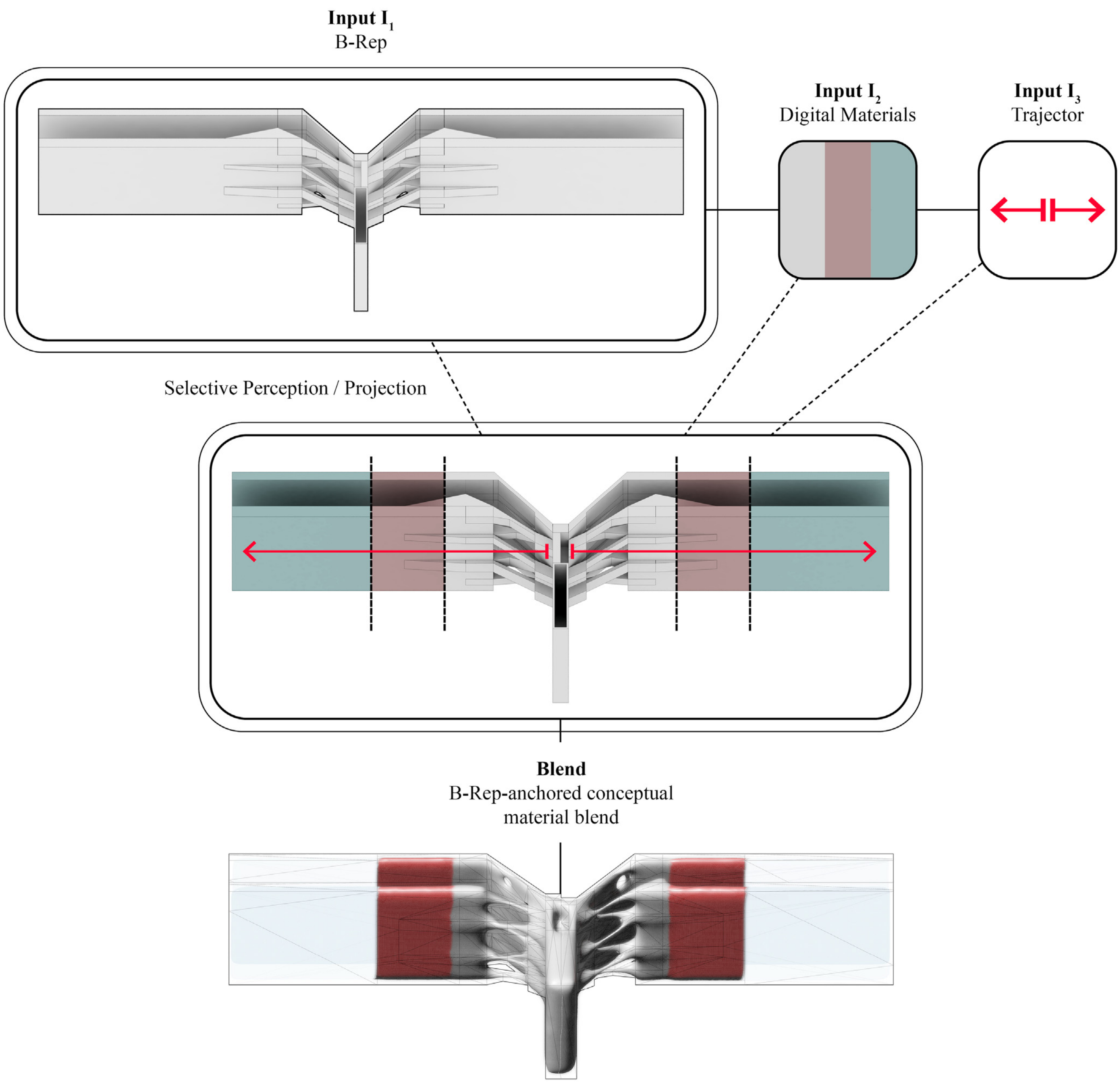

Fig. 9 Diagram of the three input mental spaces consisting of the B-Rep, digital materials and trajectors that give rise to the B-rep-anchored conceptual material blend. The rendering at the bottom is of the B-Rep filled with the five particle systems prior to the simulation.

the author's intentionality. Looking at the computational blending simulation stage of the workflow, the *relation between container* and *material behaviour*, or *human* and *material agency* is discussed through an analysis of Alberto Burri's artwork that questions concepts of control and agency. A further aim is to demonstrate how this "chrono-architecture" (Malafouris, 2013, p. 213) of FGM design operations with form, forces, and materials resembles an ecology of feedback loops of information in which mind and matter operate together synergistically. The method followed is to bring to the foreground the container (which as it will be argued is another type of agency) and discuss this against ideas of prior intention and intention in action, as well as the concept of the Background (Searle, 1983).

Additionally, it might appear that designing the container and simulating material fusion are separate steps in the FGM design process, but as it is shown designing the mould is not a linear process but one that is recursive and shaped by the characteristics of material blending within it. As it is demonstrated "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).

3.2.1. The case of Alberto Burri

Burri was attracted to the concept of "poly-materialism" and made artworks that questioned the notion of authorship. The canvas as a substrate for an artistic idea to be imprinted on was converted to a direct medium of manipulation, acquiring creative value per se. Burri used "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). For instance, in his work Rosso Plastica (Fig. 10), Burri used a blowtorch to leave a series of burn marks on a piece of plastic, which 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." (ibid., 211)

In effect, there are very similar ingredients at play with the FGM design methodology. These namely consist of *container*, *material agency*, *affecting forces*, and *human agency* or *intentionality*. In Burri's artwork, the container is the surrounding frame that holds the material in place, the material is plastic, the affecting force is fire, and the human agent is the artist 'controlling' the burning. A difference is that here, human intentionality is synonymous with 'directing' the affecting force whereas in the multi-material design process it is with designing the container.

3.2.2. Prior intention & intention in action

It can be argued, however, 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 Rosso Plastica would mean that the blowtorch fire would burn the plastic in a different manner, producing a different visual and consequently artistic result at the end of the operation. Additionally, there could also be a scenario where the combination of the blowtorch flame positioning with a specific canvas shape would make the flame spread rapidly across the plastic, subsequently reducing the artwork to a plastic lump. Or alternatively, if the canvas was held in horizontal position with the blowtorch below burning upwards, 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 is different to arranging the canvas vertically and placing the flame perpendicular to it that allows the artwork burns to spread more unpredictably (at the same time preserving part of the material intact, which was the intent).

Fig. 10 Alberto Burri's 'Rosso Plastica M3' (1961) © Fondazione Palazzo Albizzini Collezione Burri.

Here, the phrase "original intent of the artist" 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: "prior intention", as in an intention formed in the mind that precedes action, and "intention-in-action", as something that takes place in everyday scenarios where action is direct and without prior deliberation.

3.2.3. Direction of fit & direction of causation

Searle specifies the two main properties of intentionality as "direction of fit" and "direction of causation". The latter is 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" (ibid., 29). One can argue that "prior intention" is what generates an "intention-in-action", but 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. In the case of Burri, it could be that burning a piece of plastic without a particular intent generated the intent of producing an artwork about the abdication of artistic control. But it could also be that Burri had the prior intention of making an artwork that would abdicate artistic control and he used the plastic burning technique to realise that. In this case, prior intention causes an action that makes it successfully realised.

3.2.4. The background

Malafouris argues, however, that prior intention is formed by what he terms as the 'Background'. This is defined as "a set of non-representational mental capacities that enable all representing to take place" (Searle, 1983, p. 143). There is a vast array of cultural, social, and political "resources" (Malafouris, 2008) that one takes into account to form an intention. 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" and "the Italian Socialist party's election campaign in 1953"[1] (ibid., 209) among others. All the above and others are a "number of biological and cultural resources,

[1] The Italian Socialist party at the time, produced posters "showing bedraggled children dressed in rags as part of its stand against poverty." Burri's art made "associations between the stitched and frayed canvases and human poverty" (White, 2016).

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). Additionally, plastic was presented as a medium because of its increasing availability due to Italy's rapidly expanding post-war industrial sector. It is therefore not appropriate to look for the 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." (ibid., 33). Likewise, forming the intent to create a bespoke FGM workflow is only possible due to the aforementioned advancements in 3D-printing and multi-material fabrication, as well as the existence of software that allows for the digital material blending.

3.2.5. Material in tension

Effectively, it can be said that both in Rosso Plastica and in the multi-material design, the material is held in "tension" in-between the affecting force of the flame (the centrifugal force in the material simulation) and the constraining frame of the canvas (the B-rep vessel being the equivalent of this). Or for 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 counteracted with by the hands of the potter.

An initial difference in all three cases is the time frame of the operation: in the example of Rosso 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 stable centrifugal force. 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 removed as the operation takes place in the computer.

3.2.6. The extended mind hypothesis

But is there 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 design] gradually emerges in the interactive tension between the centrifugal force and the [fusion of aluminium, alumina and glass]"[2] (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 too much into glass to be continuous in a gradient manner, and therefore the result would be like an alloy as opposed to an FGM.

3.2.7. Simulation criteria

More specifically, 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) (Fig. 11):

> "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."

This effectively forms a specific piece of criteria against which to assess the result of the material simulation and eventually decide its termination. If for instance, the size of one of the sub-compartments is too wide the material contained within 'dominate' the adjacent ones and effectively form a matrix into which the other substances are diluted, becoming an alloy. Or if the affecting agency is weak, the substances do not blend and instead they form discrete volumes with a sharp boundary in between (Fig. 12). In addition, the position of the sub-compartments in the interior of the containing vessel is also important. Materials of two sub-compartments neighbouring vertically fuse better, as gravity pulls one substance downwards into the other. Additionally, a thin vessel section at the border between two sub-compartments means that there is less material to be fused and eventually not enough for an extensive gradient to be formed (Fig. 11). In all these cases, the main criterion for evaluating the resulting material arrangement is the formation of the type of gradient specified by Miyamoto et al. (1999). Achieving the right balance to attain this necessitates a synergy between all the parameters mentioned (Grigoriadis, 2019).

3.2.8. Reversal of the workflow stages

Returning to the point of agency situated in this relation between human and material intentionality and of the non-linearity of the whole design process, one could start off with the blending simulation and work backwards. A basic, almost form-less container could be used to simulate fusion

[2] The original passage is as follows: 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).

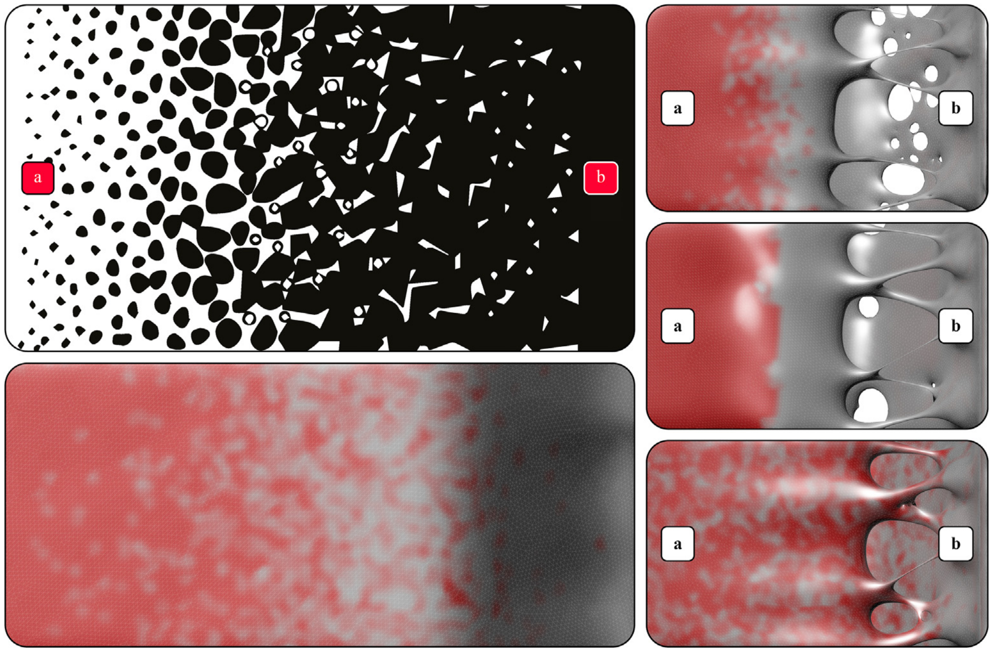

Fig. 11 Top left: "Diagram of a hypothetical graded structure, that has gradients in several different microstructural features" (Myiamoto et al., 1999, p. 42); Bottom right: The graded structure achieved in the blending simulations that has the same characteristics as the diagram by Myiamoto et al. (1999), Bottom right: Case 01 — uniform dispersal of substance a into b, exhibiting an alloy-like material distribution; Middle right: Case 02 — non dispersal of substance a into b. The two materials have coagulated before a graded material structure was achieved; Top right: Case 03 — limited dispersal of substance a into b. This is due to the thin vessel section resulting in limited material flow of a into b (Grigoriadis, 2019, p. 178).

and by observing the behaviour of materials and their self-arrangement 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 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.

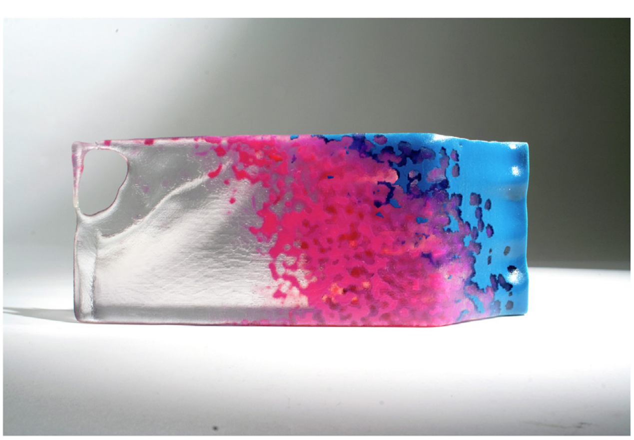

Fig. 12 A multi-material test print of half the detail shown in Fig. 6.

4. Conclusion

The advancement of 3D-printing and multi-material additive manufacturing technologies are calling for a rethinking of conventional CAD procedures. The objective of this paper in effect has been to rethink two established norms, one of the early-stage CAD design being materially disengaged and the other of a design being the outcome of the author's intentionality. Regarding the former, using the cognitive theory concept of materially anchored conceptual blending by Edwin Hutchins, it has been possible to demonstrate that the standard, material-less CAD process now takes place with material considerations that precede and succeed the B-rep design stage. Regarding the latter, using concepts of intentionality by John Searle and parts of Lambros Malafouris' Material Engagement Theory it has been possible to support that intentionality is formed in between wider material considerations, digital simulation, and B-Rep design formation. *B-rep-anchored conceptual material blending* was the original term stemming from this research, while the significance of the theoretical part of the article lies in bringing materiality back to the centre of the design process, both procedurally, as well as mentally.

Regarding the practical future implications of working with digital material entities, it can firstly be argued that the original curtain wall segment is itself the outcome of an extensive optimisation process. Parameters such as cost, material availability, component manufacturing processes, thermal performance, and ease of installation, drive its design. These, similarly, can be seen as a "questioning of authorship in the design process and lead to a repositioning of agency from the subject to the locus of engagement with" in this case not "digital materials and their affordances", but manufacturing and construction and their affordances. What changes in FGM design, however, is that installation and manufacturability have been altered completely, and are less relevant at the scale of the selected demonstrator, but for example structural performance, mass and effectively cost reduction, become the objectives of how the particle systems interact within the mould.

Here, the use of CFD is deemed necessary since as explained in Sections 2.1 and 2.2, this is the only CAD method that allows the incorporation of material properties in the formation of gradients. Of the available forces, the centrifugal one is deemed appropriate due to its correspondence to FGM manufacturing and to avoid a disconnection between the digital and physical realm. When designing an FGM for use in a building, however, there should be a correspondence between the anticipated loads that will act on that segment and the forces applied in the simulation. This way, the objectives of structural performance and mass reduction can take the lead in the design of structurally and materially optimised FGM building segments. Therefore, a TO approach (as described in Section 2.1) with multi-material optimisation capabilities incorporating (two or more) material properties, support points and measurable forces (in kN) acting on the segment, is envisaged as the appropriate method to design an FGM while bridging the physical and simulated in a precise manner. In effect, future research and development on coupling the material behaviour and multi-material interaction capabilities of CFD with the optimisation capabilities and accuracy of TO could have a significant impact on the FGM design and manufacturing field.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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