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Reframing advanced manufacturing ontologies through an exploration of ductus

Abstract: Ontologies of manufacturing and making have received closer attention in recent years thanks to a renewed interest in materiality and questions of form-emergence and form perception. This work argues that the hylomorphic ontologies dominant within advanced manufacturing can be challenged through the introduction of a "ductus" concept which relates to the traces left by unique material interactions and energy transferences as artefacts are fabricated. Drawing on multiple strands of scholarship, this paper develops a new ontological model integrating material-process relationships and end user experiences with the ductus of the making process at its core. This model is illustrated and elucidated, and the implications for design and manufacturing practitioners are discussed.

Keywords: Manufacturing ontologies; Form-emergence; Ductus; Perception

Introduction

All human-made objects in the world have a material basis and have emerged through the multifarious processes of making. The hylomorphic ontology of form-emergence – the theoretical postulate that individual being is constituted from matter (hyle) and the form (morphē) of that matter - deriving from Aristotelian thought, has exerted a substantial influence in conceptualizing artefact creation, especially in the West (Ainsworth, 2016). As will be explored, perspectives that view the designer as a master-manipulator of matter fail to recognise material and subjective perceptual experiences as actors in the processes of form-emergence too. Recent trends in design research and material culture studies have sought to challenge this perspective through several conceptual shifts of which this research will contribute. In what has been labelled the "material turn", scholarship has evolved to consider design from the point of view of makers and making cultures, materials, and manufacturing processes (Tilley, 2013; Graves-Brown, 2000). This work will offer a theoretical consolidation of multiple strands of scholarship and present a new ontology of form-emergence that challenges the default hylomorphic framing. Principally, it will critically analyse the dominant culture present within advanced industrial manufacturing of which there is a significant gap in the material turn literature.

As an initial stage, the concept of form will be explored, and a set of working definitions advanced. What is important in this discussion is how form relates to the process of design, and fabrication, and will provide a foundation for the arguments within this paper. Secondly the concept of *ductus* will be introduced. This concept, that was first utilised in linguistics for

the examination of speaking and writing patterns, will be deployed for an ontological reframing of modern advanced manufacturing technology (AMT) by suggesting that making processes themselves possess a kind of ductus of their own. This discussion culminates in a diagrammatic rendering of a novel ontological model of which the key elements are discussed in the closing sections of the paper. Finally, the implications for design culture are explored by considering how challenges to hylomorphism can allow us to rethink the acuity of human agency within the complex processes form-emergence and perhaps take a more object-oriented perspective on the creation of artefacts.

Form-emergence

Form-emergence is a challenging concept, often confusing culturally learned notions of subjects, objects and appearances. For this reason, it intersects with many strands of scientific and philosophical thought. Generally, form can relate to an underlying logic or rules-based system which defines or contributes to an overall structure. This is seen very directly in descriptions of language. What is described as the "form of the language" is a description of its structural elements: words, letters, and syntax. Essentially, form is the abstract notion of the arrangement or configuration of content. In the visual sense, form denotes an arrangement of detectable geometric elements (see Hann, 2012) or an "encounter" with the aesthetic realm (Csikszentmihalyi & Robinson, 1990). Some definitions pertain to a measurable shape or geometry, others consider form as collections of shapes or arrangements of geometric elements (e.g. Gestalt theory). Hann for example explicitly defines form as consisting of four key elements; *shape, line, point* and *structure*.

It has been argued that products are also formations of visual aesthetic elements that articulate with an idea of functional expectation. As Folkmann (2018) has suggested, the form of artefacts presents insight into how humans epistemically conceptualise the world – bounding knowledge up with functional tools. New strands of scholarship in material culture have sought to understand the human relationship with objects and why designed artefacts with varying degrees of use value are purchased and collected (Woodward, 2007). Naturally, the relationship with objects has transformed over time as a function of complex socio-cultural changes. For instance, Arnheim's (1954) work described how the experience of viewing geometry is fundamentally a process of reasoning or a kind of visual judgement. Arnheim explored a substantial number of visual perception phenomena that influence how forms are interpreted semantically and emotively. What is described as a "perceptual force" (p.6) is one of the principal concepts that gives visual perception its dynamic qualities. This force is derived from the visual context, for instance, a set of shapes may appear to have a sense of direction and movement as if being acted on by forces – the forms have a kind of telos. Speaking on the nature of form directly, Arnheim noted that form is often interpreted holistically – the doggishness of a shape will be identified before the differentiation between dogs. Furthermore, recent work in experimental aesthetics has shown how particular forms can link very strongly to particular emotional experiences – curves for example connect strongly to the subjective understanding of "positive" emotional states like joy or excitement

(Bertamini et al., 2016). The forms have a kind of inherent meaning. These observations distil how meaning is indelibly linked to form perception; the object has a teleology that cannot be separated from the object but doesn't wholly define the object (Harman, 2002; 2018). This telos – the inherent purpose or objective of an object – is an interesting place to explore form-emergence further by introducing the concept of ductus.

What is ductus?

Ductus is a kind of object teleology, but one that is removed from an explicit anthropocentric or hylomorphic framing. Scholars of material culture have spoken of a "ductus" that guides someone through an object or environment (Bø, 2017). Originally a classical concept from writing and rhetoric, ductus refers to the speed, direction and sequencing of the drawn lines or the spoken words whereby everyone has an individual and unique ductus (Kumler & Lakely, 2012). With reference to material objects, ductus can be linked to the complex array of semantic and emotional connections that are made with them. Crossley (2010) for example has applied the concept of ductus to analyse medieval architecture relating specific making cultures to unique ductus signatures or what we can call a "process-ductus". This discussion centres around developing a reformulation of making and manufacturing that highlights both the material basis of things and how this interacts with the very processes of making. Ductus, as a kind of by-word for the individuality of a particular process of creation is an interesting point in which to move away from the positivistic notions of systematic creation. Simondon (2005; 2009) for example has written at length on the processes of form-emergence and introduces a kind of ontogenic system in which form is essentially subsumed by a kind of object information. Forms grow from the information contained within other objects and interactions between objects. Relating to what Morton (2013) has dubbed an "interobjectivity" in which objects can be "birthed" from the objective influence one object may have on another, like a saw ripping through a piece of wood. The process-ductus is the telos of such an interaction.

The seeds of these theories are evident even further back in time. Nineteenth-century art critic and theorist John Ruskin (1857/2012) for example spoke of "leading lines", or lines of formation that were present within the natural world, echoing Simondon's ontogenesis and Morton's interobjectivity. The undulations and irregularity of mountains, reveals the processes of formation – *the flow and movement of energy and material*. There is a link here with manufacturing; it is possible to extend this concept to a manufactured product whereby certain markers can provide a "map" into and through the processes of making. These marks of making are generally seen as kinds of imperfections where the presence of material texture for example is obsessively removed. In advanced machining practices aided by computer-numeric control (CNC) and computer-aided manufacture (CAM) systems, the culture is orientated towards the removal of the traces of the machining process by a systematic flattening the textualities the process might create understood through a strict materialist ontology of material extraction or transformation (hylomorphism). This culture is arguably the result of, and reinforces the modern dichotomy between, science and art. Since

the European Enlightenment, the two cultures have become increasingly distinct and specialised with one grounded in positivistic conceptions of the "rational" and the "linear" with the other more "organic" or "sentimental". In design this manifests in an unwavering search for more efficient and more precise methods of producing products – where textural features are flattened by a belief in a symbolic rationalism, which is subsequently having devastating climate repercussions. As has also been suggested by Yang and Wu (2006), the modern culture of manufacturing is one of advancing efficiency and precision and not exploring the interactions and exchanges of material and process. This then accentuates a rift between the goals of human-centred design and the objectives of industrial production.

Work by Wiberg (2013) has considered how materiality could be considered more closely within design and design methodologies. This has a conceptual relationship to process-ductus, ontogenesis and interobjectivity. The proposed model accounts for non-linearity within the design process by viewing it as a dynamic exchange between *materials, details, texture and wholeness* (Figure 1).

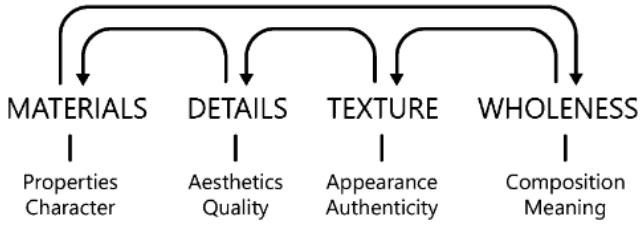

Figure 1 – Dynamics between materials and wholeness from Wiberg (2013)

In Wiberg's framing, the materials dimension should be the process of understanding a work material, its "character" and the limitation of that material. "Material character is about how a certain material can be used, what it expresses, and its inherent structure and logic" (p.630). This relates to ideas of detailing or "attention to detail" and material texture which can be interpreted both visually and through tactile interaction, sometimes to different results (Robles & Wiberg, 2010; 2011). The resulting "wholeness" is described as a kind of composition formed from the other elements taken together. This then results in a sense of meaning and completeness or as Jung and Stolterman (2012) have said, "a subjective interpretation about qualities and values of a material artefact" (p.649). From the studies in design semantics (Krippendorff, 2005), interaction and emotion (Desmet, 2003; Desmet & Hekkert, 2014; Crilly et al., 2009), it is not difficult to see how the contingencies of making and materials, have a deep influence on end user experience (see Karana et al., 2009 for instance). A process-ductus is thus a good place from which to formulate an ontology of emergence.

Exploring the model

The new ontological model is presented full-page in Figure 2. In essence it provides an alternative framework in which to consider the processes of form-emergence by highlighting the links between process-ductus and the experiential properties of an artefact including

affordance theory (Gibson, 1979; Norman, 1999), design semantics (Krippendorff, ibid) and design-emotion (Desmet, ibid). Additionally, it is explicitly intended to inform the future development of CAM systems and process control systems more generally by highlighting the importance of perception and materiality and how it is intimately related to the processes of making. While there is always a ductus (telos or narrative) to a making process, this ontology subverts the standard hylomorphic conceptions of emergence by highlighting how when a material is shaped by a tool the material is also working against the tool in a process of exchange, and it is within this dynamic, this interobjectivity, that the perceptual qualities of form (tactility, aesthetics) derive.

Firstly, the dynamics of form were considered and cast as an integral part of what has been labelled "form-emergence" where form is not imposed but grows from complex meshes of causality. This form-emergence is not a fixed state of material physicality but interacts with the subjective feelings that constitute the user experience of an artefact. Wiberg (2014) has argued that "wholeness" originating in a subjective experience of material meaning is connected to the appraisal of material through aspects of texture and detailing. This results in notions of authenticity and aesthetic quality entering the overall judgement of an object (artefact materiality). Thus, the modelled ontology shows an interaction between form-emergence, artefact aesthetic and artefact materiality. This goes beyond the standard design methodologies and beyond standard conceptions of design for manufacturing. While links between these factors are casually drawn between these elements, they are rarely addressed at the level of ontologies of emergence, and there is an assumed linearity of creation starting with the designer-agent (hylomorphism).

The model also considers the interaction between ductus and materials and between ductus and the intensions of the designer. Material inputs will always have sets of mechanical parameters that may be more flexible or more constrained but the interaction between this and the process, in part, defines the nature of the emergent artefact. It is also an interaction based on convergence, what Simondon (2005) called the unity of "transformational half-chains". This element is critical as it re-establishes the importance of material and process forces and the primary roles they play in how ductus can be understood.

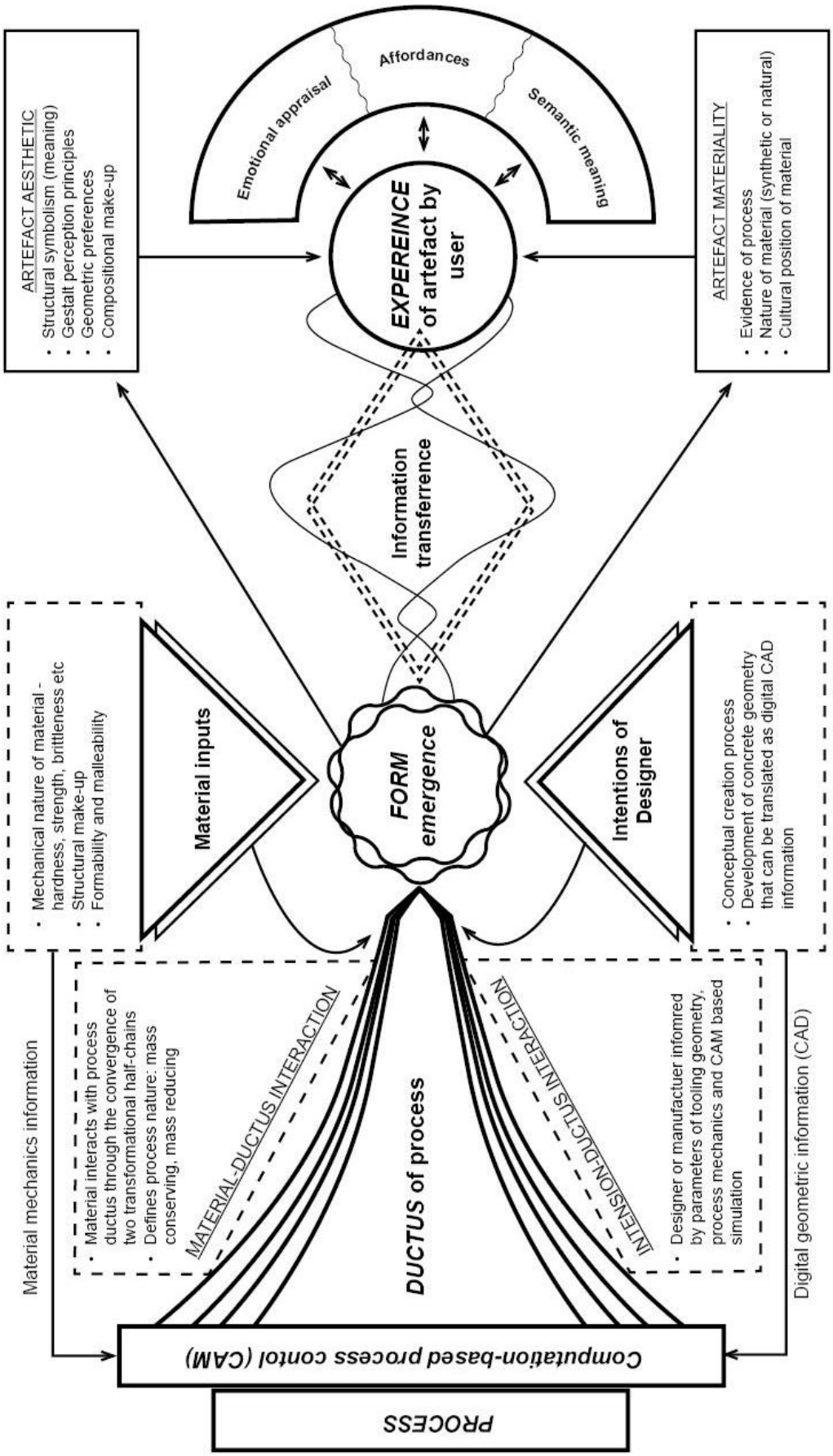

Figure 2 - Proposed ontology of emergence for AMT including process-ductus, form-emergence and user experience of artefact

Ductus within advanced manufacturing

Ductus is modelled in Figure 3 as the strongest and most fundamental aspect of this ontology of emergence which focuses on advanced manufacturing technology. If we can establish ductus as a kind of imprint or trace left by a process, the telos of a process, in what ways can this be applied to a general discussion of AMT and the perceptual properties of objects produced through such methods?

Within the context of craft, ductus may be easier to establish whereby each individual maker will impart individuality upon the object. Advanced modern processes are different in one critical sense; the processes are usually mediated by computer systems. CAD and CAM used in conjunction, allows a manufacturer to make digital representations physical. Though these digital systems are an extension of human intentionality and the manufacturing machines extensions of tools. Ductus can thus be identified (within the context of AMT) at the intersection between concept and process, articulated by a computer system that provides control over the parameters of making. Form-emergence is accordingly bounded by material inputs, conceptual design intentions and the making parameters. Simondon (2005; 2012), in his critique of hylomorphic models of emergence discussed how not only do tools work against material, material works equally against the tool. This can be extended to this discussion around process-ductus: as the forming tool meets the material, guided by a digitally bounded process-ductus (e.g. CAM software), the material also meets the tool as a kind of oppositional force or what Simondon described as a convergence of "transformational half-chains" (p.41). In Ingold's (2012, p.433) discussion of this, he describes form-emergence as the consequence of a "field of forces" where the emergence is described a kind of "transitory equilibration".

The CAM programme acts as a mediator between the material and the process, allowing the digital design conceptions to be readied for the process - compatible with the technical constrains of the manufacturing system – but also allowing the process (the machine setup) to be readied for a material input. Deleuze and Guattari (2013, p.409) describe form-emergence as a process of "perpetually variable continuous modulation" citing Simondon's influence. In the context of something like CNC machining, this modulation lies in the interaction between the cutting tool and the material mediated by a CAM system. This is illustrated by the diagram in Figure 3 where form-emergence is not ontologised as a point-to-point transition from CAD information to CAM system to process to material, but as a multi-directional transference between material, geometric information and process parameters. The interaction between these properties defines the process-ductus. Ultimately it is the material and the process-ductus that underlie the form-emergence or as Ingold (2013, p.434) has stated; "iron flows, and the smith has to follow".

CNC machining for example leaves traces in the form of lines and other kinds of markings on the work piece, sometimes these are very detectable but are usually removed through post-process polishing or finishing operations. These marks and lines imbue a kind of temporality onto the artefact in the same way that the act of drawing leaves a dynamic and temporal

trace providing insight into the historic motion of the drawer or the ductus of the drawing process. The marks provide a direct insight into the motions of making conducted by the machines, a machine teleology. These motions also contribute to a form-emergence and within the context of AMT are strictly controlled within a framework of Cartesian coordinates. The next relevant question is whether this bounded computer system can in any way be ontologically equivalent to the more direct work of the human hand. Despite some forceful argumentation from thinkers such as Ingold (2009) and Pallasma (2012), the picture is not exactly clear. These discussions go some way to argue that even within a bounded computational system where a process is mediated by digital simulation, different vistas of material experience can be created. Figure 3 shows this dynamic at work – a process of form-emergence mediated by a system of technical control of process (CAM).

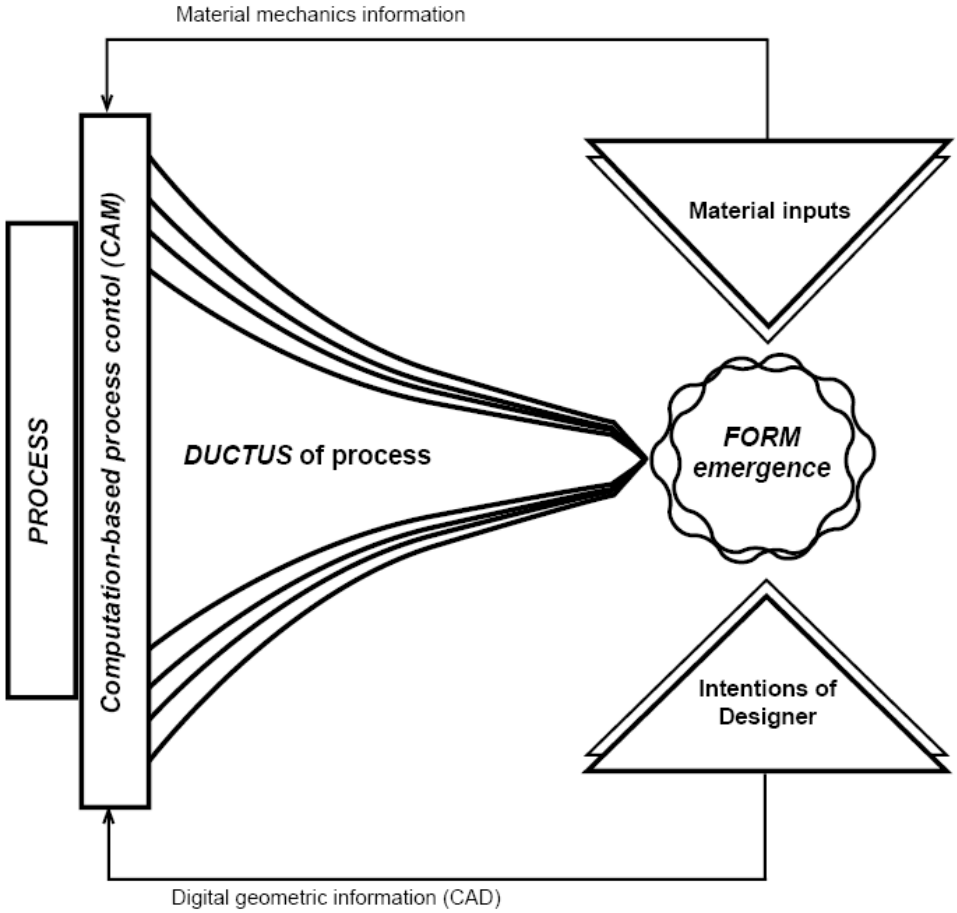

Figure 3 – Ontological basis of form emergence in the context of AMT founded upon process and process-ductus with material and intentional inputs also mapped

Ductus, emergence and human-centred design

How can these conceptions of process-ductus be integrated into wider design theory? And what implications can this have for human-centred design (HCD) thinking? Reconsidering ontologies of emergence and creation can allow us to think about new means of industrial production, tailoring processes around specific human or environmental needs. So far, we have seen how the control of process that is afforded by CAM technology can be reframed

within a new ontology for manufacturing. The critical component in the new ontology is how process-ductus influences form-emergence and interacts with other factors such as emotion and semantics. There are several critical ways in which this ontological reframing can influence HCD thinking. The "dimensions" that Moggeridge (2007) introduced in order to delineate the relationships between the physical dimensions of a product (its physical form) and other qualities of product use (meaning, time and behaviour) is instructive. Interaction design is philosophically and practically important for HCD as it allows for the tuning of products to be better understood functionally and more pleasurable to use, following Jordan's (2000) framing. Introducing the ductus concept benefits this philosophical position by configuring form-emergence within a system of material-process interactions that can be partially controlled using technology such as CAM software. Human-centred approaches favour design outcomes that are highly attuned to specific user groups or specific needs (Giacomin, 2014). By establishing a process-ductus, aspects of form, aesthetics and tactility can be addressed in a more controlled and direct way enhancing what Norman (1999) calls "real" or "detectable" affordances.

As a related mode of design thinking, Kansei engineering can also be enhanced by the introduction of a conceptual process-ductus. Kansei design thinking posits that products and services can be edited or reconfigured to achieve more positive experiences for users, and is in this sense, human-centred (Schütte et al., 2004). Critically, the Kansei methods are reliant on the integration of semantic theory (interpretations of meaning) with practices within product engineering (e.g. fabrication processes). Specifically, Kansei engineering develops attuned psychological and physiological experiences based on focused user testing (Nagamachi, 1995). Ontologically, the methods are framed from a perspective of psychological responses to form, aesthetics and function but usually not from responses to specific material properties or properties associated with processes. Introducing ductus into this perspective advances the scope of Kansei methods allowing the intrinsic aspects of processes to be utilised for attuned psychological and ergonomic design. The interesting studies from Niedderer (2012) demonstrate that manufacturing processes can be configured to deliver enhanced emotional responses, engagements and innovative functions. Accordingly, the resultant product or object experiences are richer because of these ductus-focused making perspectives.

Dynamics of form – experience and emotion

Figure 4 shows in more detail the element of the ontological model linking form-emergence with the experiential facets of artefact use (emotional appraisal, affordances and semantic meaning) through a process of information exchange. While the epistemic basis of emotion is a topic beyond the scope of this paper, phenomenological arguments can be explored. John Dewey (1934), in his philosophical study of the aesthetic experience spoke of emotional transience and a shift between emotional states which is instructive:

> "We are given to thinking of emotions as things as simple and compact as are words by which we name them. Joy, sorrow, hope, fear, anger, curiosity, are treated as if each in itself were a sort of entity that enters full-made… In fact emotions are qualities… of a complex experience that moves and changes." (Dewey, 1934, p.41)

In developing this alternative ontology, the emotive and semantic associations of form must be considered. If we take a form-emergence phenomena, that is facilitated by machine engagements and processes of making, as an initial starting point, an element of a new ontology can be examined. The critical dynamic is one of exchange whereby the experiences associated with form engagement or interaction (emotion, semantic interpretation and so on) are both informed by and an influence on the form itself. The process is bidirectional where the qualities of experience change the nature of an object's formal qualities; the way illusion can reveal symbolic values in form and symbolic values can stir emotion. All of this is fundamental to a process of form-emergence that Ingold (2009) has stated is contingent upon flows of material and energy but is also bounded in an ontology contingent upon flows of emotional experiences, semantic meanings and identified affordances. It should also be noted that what we might call the "architecture" of experiences or the conditions which produce and inform it, exist *prior* to the form itself and exist in a space somewhat detached from the process of form-emergence (Figure 4). They are however the foundation of the experience of the user – existing in a kind of superposition, not intrinsically a part of an artefact but also not entirely removed from it. For example, the experience of an object appearing "cute" depends on a pre-existent nexus of cultural and psycho-social arrangements that the made object is both dependant on and outside of. At this point we can explore some of these observations more deeply.

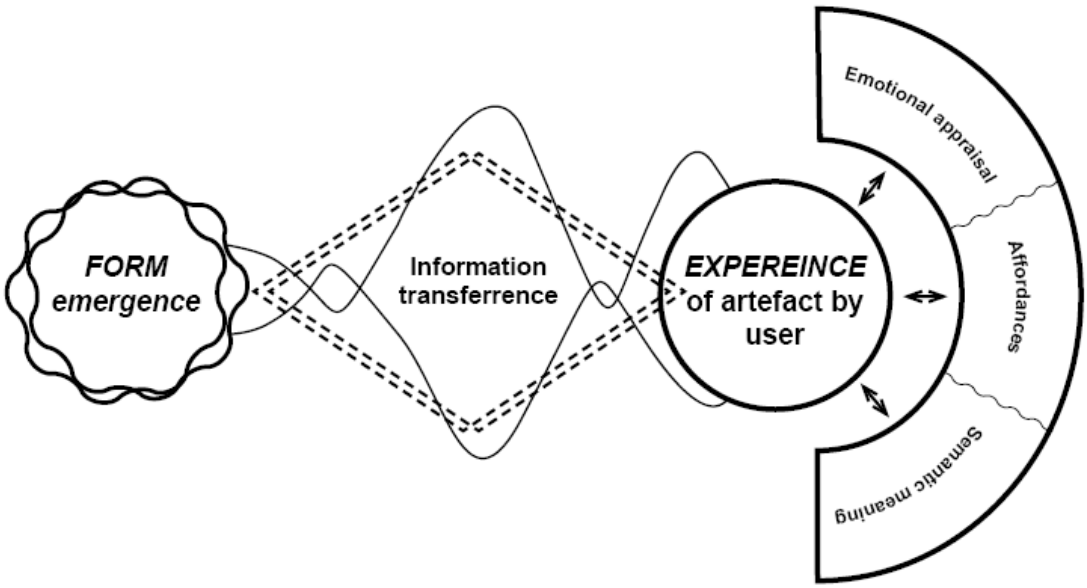

Figure 4 – Ontological basis of form-emergence with respect to the subjective domain of user experience including emotions, affordances and semantic meaning of artefact

Implications for design practice

This ontological reframing presents further questions for us. Critically, what is the primacy of human *agency* within the design and making process? Ultimately this amounts to a challenge to human agency and status and relates more specifically to the metaphysical concept known as the "*will*". The will, defined as the mysterious inner essence of the world by German philosopher Arthur Schopenhauer (1818/2000), who believed that the exploration of making practices such as craft was a means of transcending the *will*. In design terms, we can relate this to the obsessive desire for perfection in industrially manufactured products. While a process-ductus will produce a trace or footprint, the dominant hylomorphic culture would rather it not exist so that the processes could more reliably replicate human impositions on matter – an "objectification" of the will in Schopenhauer's terms.

Throughout, this paper has argued that the hylomorphic designer-agent model of form-emergence is problematic. In essence, agency is indelibly linked to the processes of form-emergence – in the presented ontological model this is recognised as the input "designer intentions". But the *will* can potentially be transcended. Instead of thinking in terms of transcending things vertically, the idea of flattening or equalling is perhaps a better approach. Graham Harmar's (2002; 2018) interesting philosophical developments in Object-Oriented-Ontology (OOO) is at this point instructive. OOO posits that the ontological relations between a human subject and an object, traditionally thought of as higher in status than that of object-object relations, can be flattened or made equivalent. This flat ontology presents space to move away strongly from hylomorphism. In advanced numerically controlled processes, the relationality between the human subject and the object being created or emerging becomes in some sense disconnected. As such the *process-material,* or *object-object* interaction becomes paramount, becoming equal in ontological status to the intentions of the human actor. This is part of what the presented ontology is illustrating. The principle of ductus is essentially the interface between the subject-object/designer-agent relationship and the object-object/process-material relationship. Furthermore, the interobjectivity that Morton (2013) has described translates human intentionality into an "object" that can interact with other objects. This mesh of object interactions results in the birth of new objects: paradoxically both distinct from and part of the processes that created them, what Morton has called the mysteriousness or "magic" and the heart of things. Process-ductus is thus both a description of object interactions as artefacts emerge, and a trace or footprint left by these interactions.

In terms of design and production, the desire to make perfect a product removes its ductus, severing any ties the user may have to the processes of making and emergence. Given the process control capabilities in advanced manufacturing techniques, there is significant scope to expand the ontological window in which systems like CAM operate facilitating a direct connection between a user and process-ductus. The ontological reframing also presents the possibility that human-factors questions relating to user interaction, semantics, emotion or

aesthetics could be tied to a process-ductus explicitly. For instance, the trace left by a machining tool on metal could be attuned for a particular set of emotive or semantic responses adding additional layers of meaning for users. Such principles have already been explored by Karana and others (2009), but this would constitute a next step whereby the relationalities between process, material and user-experience form part of future CAM systems.

Conclusions

This paper has presented an alternative ontology for manufacturing processes centred around a "ductus" concept. Ductus is a teleological concept that individuates processes by the unique signatures they leave, like the distinct style of a painter or drawer. By firstly showing that concepts of form and form-emergence are complex and may indeed have a kind of inbuilt purpose or telos, the idea of a telos focused manufacturing ontology was advanced. As industrial manufacturing tends to be linked with positivistic notions of engineering efficiency, this was identified as a significant gap whereby a novel ontology of emergence could be a useful reframing.

By extending the concept of ductus to the realm of making and materiality, the concept of "process-ductus" was introduced. The process-ductus is the unique signature of the process, the way energies and materials are exchanged and the resultant traces that are left from the processes of creation. The new ontology was developed centred around the ductus of process whereby the hylomorphic designer-agent views of creation are challenged by placing them as a secondary object in a wider exchange of material interaction and flows of energy. This is seen as a kind of ontological flattening where the status of the human creator is diminished to an object in a mesh of other interacting objects, following the Object-Oriented Ontological philosophical framing. The implications in thinking about design at large and how process-ductus could be applied within the existing architectures of human-centred design thinking was additionally discussed with an explicit suggestion that CAM systems could be rethought to integrate ductus.

Furthermore, what this ontological flattening achieves is a reframing of "advanced" manufacturing processes to something akin to *craft* whereby designer-agent intentionality is stripped of its status and the elements of process and material are elevated following Simondon's concept of individuation through ontogenesis. The ductus-based ontology seeks to reframe human agency, levelling the ontology of emergence and reinstating value in non-anthropocentric emergence and the related artefact "imperfections" that themselves may link to rich emotive experiences and the embodiment of distinct meanings for the people or other lifeforms who may interact with them. In design and production terms, this offers space for the reinvention of CNC or CAM systems, allowing for an integration of the complex relationalities between process-ductus and user experience.

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