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Enactive individuation: technics, temporality and affect in digital design and fabrication

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Abstract The nature of creative engagement with computers and software presents a number of challenges to 4E cognition and requires the development of analytical frameworks that can encompass cognitive processes as they extend across material and informational realms. Here I argue that an enactive view of mind allows for better understanding of digital practice by advancing a dynamic, transactional, and affective framework for the analysis of computational design. This enactive framework is in part developed through the *Material Engagement Theory* (MET) put forward by Lambros Malafouris, in part from the phenomenologically inspired philosophy of Bernard Stiegler. Both advance temporality, technics and technique as key to understanding human creative imagination and their work can support each other in different ways; Stiegler allows for a theorisation of digital tools largely missing from the cognitive archaeology of Malafouris, whilst Malafouris provides a cognitive theory to further develop key ideas in Stiegler's philosophy. Bringing their work together through Gilbert Simondon's theory of individuation, I develop the concept of *enactive individuation* and apply this to the analysis of a case of robotic design and fabrication from my fieldwork with digital architects and engineers. This case allows for further exploration of how enactivism might productively be extended into the digital realm by underscoring the explorative engagement at heart of even highly systematic work with computers and software.

Keywords 4E cognition · Enactivism · Extended mind · Material engagement theory · Digitial design · Architecture · Software · Bernard Stiegler · Gilbert Simondon · Individuation · Affect

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1 Introduction: Mind and creativity in digital work

The aim of this article is twofold: First, I seek to extend the frameworks of material engagement theory developed by Lambros Malafouris (MET for short) into the realm of digital creative work using a case of computational design and robotic fabrication. There are few examples of insights from 4E cognition used in analysis of human engagement with digital tools but I want to argue that this is entirely plausible and that the enactive frameworks of MET can help solve a number of issues around the extension of mind into the digital realm. Second, I seek to introduce the concept of *enactive individuation* to argue for the value of a processual and temporal perspective for understanding cases of computational design thinking: MET's inherent focus on shifting temporal registers can help explain the efficaciousness of digital engagement by bringing together the specifics of digital modelling practice with the affective experience and history of design teams and individual designers. In this, I draw on Bernard Stiegler's phenomenology of technics[1] and time to discuss the transformative relationship between technics and cognition; and further seek to show how the enactive frameworks of MET can throw new light on Stiegler's concepts of *grammatization* and *epiphylogenetic memory* by drawing attention to how time and affect are enfolded within enactive individuation in computational design and fabrication.

The article proceeds through a brief introduction to contemporary practice in the fields of computational architecture, design, and fabrication and the challenges they pose to 4E cognition. An enactive perspective on cognition seem particularly well-suited to explain the explorative nature of computational design research. To address this while developing a phenomenologically inspired account of our affective engagement with computers, I present Stiegler's (1998, 2010, 2013) philosophy of technical genesis of human experience. Stiegler does not explicate a cognitive framework underlying the creative entwining of mind and technics in his work, however, key concepts of MET (Malafouris 2013, 2014, 2015), specifically the notion of *hylonoetic fields*, can provide an explanatory framework for understanding the cognitive entanglement of mind and technics. I seek to bring MET's enactivism into the philosophy of technics by showing its complementarity with the concept of individuation, which underlies much of Stiegler's thought. I bring these perspectives together in the notion of enactive signification and apply this to analyse a case from my fieldwork on digital design and robotic fabrication to show how a radically extensive and enactive framework offers a way forward for analysing computational design thinking. The temporal and affective perspectives at the heart of MET and enactivism become key for this analysis of enactive individuation in digital practice, and supports a wider discussion of enactivism, mind and affect in digital society.

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[1] The word *technology* fuses the Greek root *tekhne* (art or craft) with *logos* (discourse, branch of learning), a dual meaning that is often downplayed (Stiegler 1998:1 cf. Marx 2010). In this sense, 'technology is to technics what linguistics is to language, what every science is or would be to its objects', writes French anthropologist François Sigaut (Sigaut 1994:422). Technique and technics are material engagements with the world that we can know by the change they effect in people and their surroundings. They emerge as social goals take the form of material needs and crystallise in infrastructure, expertise and practices; by enquiring into the tekhne and logos of this nexus, we can begin to understand the deep entanglement of human mind with our material and technical milieus.

2 The challenge of computational design thinking to 4E cognition

Computing power and sophisticated digital tools are changing architecture. Scripting, software and new fabrication technologies offer unprecedented opportunities for tech savvy designers and hold the power to fundamentally re-structure design practices. Increasingly advanced tools – from computational design modellers to robotic fabrication – play decisive roles in architectural design, leading to a profound questioning of relations between creativity and technics, geometry, data, tectonics, and materials (e.g. Oxman and Oxman 2014; Menges 2012; Picon 2010; Terzidis 2006; Kolarevic 2003). Tools for handling complex geometry and large data sets are used to create new, expressive and dynamic designs such as the undulating forms of for example Zaha Hadid Architects. Their use of continuous curvature and surfaces are amongst the most well-known examples today, but this is a general feature of much digital design, made possible by computational design tools. These tools let designers build intricate models, where geometry translates to data, and data to geometry. This shared informational basis permit functional integration across a wide range of software environments allowing for modular manipulation, combination and re-use of inputs and outputs from computational models across all phases of architectural design and fabrication. Computational tools allow for intuitive creation of advanced 3D geometries and integrate the mathematics and vast numerical calculations that often underlie these into digital models that expand from being design tools to also encompass construction details and the creation of fabrication ready geometry for 3D printing or robotic fabrication (Søndergaard et al. 2016, Brander et al. 2016, Grigoriadis 2016, Menges 2015, Dörstelman et al. 2014, Parascho et al. 2015, Burry 2002). The data-driven modularity and associative logic driving these tools highlight form-finding over form-making as computational design models take on a life of their own and can be moved and manipulated according to logics beyond the initial conditions of their construction. Architects Achim Menges and Sean Ahlquist (Menges and Ahlquist 2011:16) propose that a deep understanding of how these integrative models operate, as form and as mathematical ordering constructs, is fundamental to computational design thinking.[2] In this, the position of the designer is changing, explains Menges and Ahlquist, as computational design relies on the purposeful creation and execution of rules for the development of form, but often not exhaustive descriptions of final forms themselves. This shift from finished object to process, from free-form design to rule-based exploration, is at the heart of digital design[3] and presents and interesting challenge for philosophy of mind in explaining exactly how imagination and creativity emerge from computational design research.

In this paper, I present a top level analysis of a computational design and fabrication workflow to show how this might proceed. The analysis is drawn from an ongoing robotics R&D project, which forms part of my fieldwork with digital architects and engineers. This project seeks to combine research into 3D modelling, advanced mathematics, materials science and robotics to reduce the high prize of realisation for complex architectural geometry. The use of advanced geometry is on

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[2] The concept of 'computational design thinking' is adapted from Menges and Ahlquist (2011) to describe design practice that is oriented towards constructing computational systems leveraging clearly defined parameters, and associative logics and feedback between them, in open-ended exploration of the possibilities of technology and form.

[3] cf. Cross 2006:32, Simon 1996:124 for earlier theories of design thinking iterating similar arguments.

the rise in architecture thanks to computational design tools (e.g. Burry 2011a), but is often prohibitively expensive to construct due to the need for creation of bespoke formwork for casting concrete into undulating forms. Addressing this, the project pioneers the use of advanced robotics for automated fabrication of moulds for casting curved surfaces in concrete. It leverages the ability of computational design tools, as highlighted by Menges and Ahlquist, for integrating heterogeneous parameters into flexible models while bridging the fields of design and fabrication. Utilising the fact that the properties of a bendable and heated metal blade can be described and controlled numerically it automates a setup of three robots for cutting moulds into blocks of expanded polystyrene (EPS) at high speed, flexibility, and precision – in essence creating a cheap, fast and reliable file to factory alternative for fabricating advanced formwork for a more expressive architecture.

This and similar digital platforms for computational design and fabrication call for an open-minded, interdisciplinary anthropology capable of investigating what digital change means for our understanding of natural and informational environments and for our cognitive interactions with technology and each other. This raises a number of questions with pertinence for ongoing discussions in extended mind and 4E cognition (Menary 2010): what are the theoretical, methodological and empirical commitments of taking computational tools and artefacts seriously? How might we begin to make sense of cognitive ecologies that are at once material and informational (Hutchins 1995, 2010, 2014; Poulsgaard and Clausen 2017)? How do these ecologies shape architectural imagination and practice as minds stretch across them? What becomes of the social role and embodied skills of the designer? As I hope to show, answers to these questions have deep consequences for the philosophy of mind. Proponents of computational design research in architecture have been dealing vigorously with these questions for some time (e.g. Burry 2011b; Menges and Ahlquist 2011; Oxman 2008; Davis 2013; Thomsen et al. 2015) and while highly varied, cases from digital design and fabrication offer a privileged site for exploring cognitive theories that seek to better incorporate digital practice; in turn, current debates in the philosophy of mind and phenomenology of technics promise to cast new light on the nature of creativity and material engagement in computational design work. There are few examples of 4E cognition taking on the challenge of digital thought and action (see Clark 2003; Edmonson and Beale 2008; Alač 2011; Clowes 2015). In this paper, I hope to show how the frameworks of enactive and embodied cognition can overcome these challenges by pushing key concepts of MET (Malafouris 2013) into the digital realm to better understand how digital tools transform creative imagination. There is a clear historical element to this analysis, but rather than attempting a broad historical overview of digital design in architecture (see Davis 2013; Carpo 2012; Burry 2011b), I seek to investigate how shifting temporal registers come to influence tool use in the here and now by attending to the multiple temporalities enfolded within computational design models. This situated temporal perspective draws in part on Bernard Stiegler's (1998, 2010, 2013) philosophy of technics, in part on the cognitive archaeology of Lambros Malafouris (Malafouris 2013; Malafouris 2015; Gosden and Malafouris 2015), and in part on ongoing fieldwork within architectural design research (cf. Poulsgaard and Clausen 2017).

3 Stiegler's evolutionary phenomenology of technics and time

Bernard Stiegler (2010, 2013) is deeply concerned with how processes of digitisation affects human thought and action. Inspired by Heidegger and Gilbert Simondon, he argues for a phenomenology of technics where the very evolution of technology gives rise to the human condition and fundamentally frames our view of the world. This originary and inextricable relation further extends to our experience of temporality and (in a departure from Heidegger) Stiegler posits that the only access to an affective and authentic experience of time is via technics as technology and objects are necessary mediators of our relation to both past and present (Stiegler 1998:135). Humans and technics co-evolve; had we not used the tools we had, we would not have become who we are and, as for the blind man with his cane variously discussed by Merleau-Ponty (2005:165) and Bateson (1972:324) it makes little sense to ask where technics stops and human begins in this existential entanglement. For Stiegler this interdependence extends to all of us, *all the time*; we are all, always and already, extending our bodily and cognitive faculties via technical prostheses. In this perspective, we cannot escape the deep historical and transformative influence of technics as little as we can escape the evolutionary history of our species. They inextricably entwine; technics is a constantly evolving prosthesis for the creative extension of our embodied and imaginative abilities, including the ability to anticipate (design) and implement (fabricate) different futures.

The concepts of *grammatization* and *epiphylogentic memory* are key to Stiegler's evolutionary analysis of technics. He adapts the concept of grammatization from Derrida to describe technical processes that formalise human behaviour and expression through e.g. script, mechanics or code. For Stiegler (2010, 2012, 2013), the concept of grammatization thus denotes processes by which material, sensory, or symbolic flux is made discrete, spatialized and reproducible. Analysing Plato's *Phaedrus* alongside Derrida, he points to writing as the originary moment of grammatization. Derrida's (1983) inquiry into the ambiguity with which Plato approaches writing points to an essential duality of all technics for Stiegler: writing frees speech from continuous time, a powerful invention, but writing also erodes memory by fundamentally transforming the context for human thought and expression. Script makes speech discrete, spatialized and reproducible in new contexts and places. It also obliterates the affective transformative experience of learning *by heart* which was key to human creative cognition for millennia. In this sense script is both remedy and poison, an essential duality Derrida (ibid. 98) locates in the word *pharmakon*, which is used to describe writing at different places to different effect in Phaedrus. This *pharmacological*[4] nexus of technics, memory and affect animates Stiegler's thought and becomes key to his evolutionary analysis of the human qua technics. For Stiegler, the multifaceted nature of technics carry a specific kind of externalized memory; an ongoing process of exteriorisation that is not just an accidental effect of our species evolution, but the driver of this evolution (Stiegler 2013:34). The externalisation of memory in technics is separate from internal, individually acquired memory (what Stiegler calls epigenetic memory) as well as the

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[4] This pharmacological aspect extends to all technology for Stiegler, who put forward digital technics as the latest stage of writing and therefore an essential scene for the potential destruction or rebirth of mind (Stiegler 2013:30).

phylogenetic, or biological evolutionary, memory that we inherit from our ancestors. Rather technics, technique and language denote a further technical layer added to the individual and species level, and this he calls *epiphylogenetic memory*. For Stiegler, we are *defined* by processes of epiphylogenesis, the exteriorisation of memory in technics and interiorisation of these memories through technical practice (Stiegler 1998:140). That is, we are defined by specific historical processes of exteriorisation – or extension of mind – that rests on accelerating processes of grammatization whose current reach and scope vastly exceed anything we have seen before.[5] The modularity inherent in digital code and computational design supports the inclusion of any number of symbolic and technical gestures whether these relates to a Socratic dialogue, advanced geometry, material or movement; in every case a continuous flux is broken down into a system of discrete elements, data that can travel and be manipulated and combined according to new logics (cf. Menges and Ahlquist 2011). With this in mind, computational design and robotic fabrication entails a simultaneous grammatization of design intent, material properties, movement and complex mathematics amongst others, and for Stiegler, the stakes are high as grammatization and epiphylogentic memory determine our capacity for creative and social thought.

In a very real sense, technics forms the horizon of our imagination, our creative engagement with the world around us and our perception of temporality. If we take this seriously, it is obvious that the nature of our technical prostheses profoundly impact the nature and scope of our creative imagination. I will argue that the systemic integration at heart of computational design thinking draws its efficacy from this logic underpinning Stiegler's concept of grammatization and epiphylogenetic memory, such that one might be deployed to better understand the other. I agree with Stiegler, when he argues that digital grammatization radically transforms our social and cognitive environments and believe that his phenomenology of technics, memory and affect holds great explanatory power for understanding our current digital moment. But in order to fully penetrate into the synthetic and digital nature of computational tools and thinking, we need to attend to the logics and differences driving specific processes of digital grammatization and ask how they come to influence mind. Stiegler does not make the cognitive framework underlying his analysis clear (see Reveley and Peters 2016), and so at least two sets of questions arise from this; one has to do with developing a cognitive theory to explain the efficaciousness of Stiegler's concepts of epiphylogenetic memory and exteriorisation; the other with how philosophy of mind might theorise the fundamental cognitive coupling of technics, affect and time. Below, I introduce the frameworks of MET and develop the concept of enactive individuation to help answer the first set of questions and set up a discussion of the second.

4 Material engagement and enactive individuation

MET introduces a relational theory of being in the world where mind, technics and technique – or material engagement – are ontologically inseparable. Similar to

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[5] If the industrial revolution entails an unprecedented moment grammatization of bodily movement and skill through its mechanical reproduction of the gestures of workers, current developments in genetics and bioengineering centred around the reproduction and revision of cells using e.g. CRISPR technology entails grammatization of the genome, if not life itself.

Stiegler's phenomenology of technics, MET seeks to overcome Cartesian dualism and anthropocentric analyses of material culture by instigating a number of transgressions on the Cartesian subject. It radicalises theories of extended mind to collapse hard distinctions between internal and external cognitive processes; it puts forward a relational perspective on agency and intentionality; it develops a theory of the material sign and introduces the concept of enactive signification to explain the constitutive entwining of mind and world. MET also adds a unique temporal perspective to current debates in the philosophy of mind as it pursues these conceptual transgressions across a variety of domains and time-scales to explain the evolution of mind qua shifting cognitive and technical ecologies (Gosden and Malafouris 2015; Walls and Malafouris 2016; Poulsgaard and Malafouris 2017; cf. Gosden 2008). Above all, MET champions a relational approach to thinking and doing. What this means is that human creative thinking becomes a fundamentally situated activity where mind emerges through dynamic interaction of bodies, materials, and symbols. As already intuited by Menges and Ahlquist, our creative imagination is bound up in perpetual interaction with heterogeneous systems reaching across material and symbolic realms. Radicalising this perspective, MET proposes to move beyond more conservative theories of extended mind (Clark and Chalmers 1998; Clark 2008), by rejecting mental representations and content while shifting the gravitational centre of mind away from the individual (cf. Gallagher 2013, Hutto and Myin 2013:152, Di Paolo 2009). Deprived of content, mind becomes emergent and enactive. Inherently extensive rather than occasionally extended.[6] Malafouris (2014) puts forward the analogy of a potter at the wheel to explain the dynamic exchange between matter, body and mind. The potter cannot simply create a pot from an initial mental image of it; instead, he has to feel and follow the clay as the pot emerges through this dynamic transaction. The same goes for mind; it is not just the pot that is emerging and undergoing continuous change, but also the potter's ideas of the pot (Malafouris 2014:145). Mind and creative imagination emerge in dynamic coupling between heterogeneous forces playing off each other's strengths and weaknesses in embodied practice. There is an explicit critique of hylomorphism here, extending a line of thought from Gilbert Simondon's philosophy of individuation (Simondon 1992, 2008; Combes 2013; Scott 2014). MET seeks to restore dynamic life and potentiality to materials and alerts us to the fact that the creation of form is not, as hylomorphism would have it, a question of abstract ideas being imposed on inert matter; rather it is one of form and ideas emerging through continuous and lively interaction. Simondon's critique of hylomorphism is bound up with his concept of individuation defined as the 'critical moment when unity and coherence appear' from out the flux of potentiality inherent in any mixture; he reproaches hylomorphism for obscuring this moment by presupposing that which it seeks to explain (form, object, person, etc.) effectively hiding the anterior process of individuation (Simondon 2008). Instead, he suggests, we should seek: "*to understand the individual from the perspective of the process of individuation rather than the process of individuation by means of the individual*" (Simondon 1992:300).

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[6] MET positions itself in the radical enactvist camp (Hutto and Myin 2013; Gallagher 2013; Di Paolo 2009; De Jaegher and Di Paolo 2007; Varela et al. 1991) against cognitivist theories of mind and content; to be sure, humans may be able to construct mental representations of most things, but we might not need these for many mental functions if we instead recognise that material engagement acts as a fundamental cognitive resource in its own right – that we think with and through things in action.

For the present argument this adds a further affective dimension to the relational ontology of Stiegler and Malafouris, highlighting that no individual – idea, geometry, person – can exist outside this entanglement with a milieu that is its complement. Individual and milieu emerge simultaneously from the tension inherent in individuation, they are both partial and connected results of the creative interaction of bringing forth, what Simondon calls the essential: "*procedure of the mind as it discovers. This procedure consists in following being in its genesis, in carrying out the genesis of thought at the same time as the genesis of the object is carried out*" (Simondon in Combes 2013:7).

Moving along similar relational and dynamic lines, Malafouris (2013:226) advance the notion of *hylonoetic field* (from the greek *hyle-* or matter, and –*nous*, mind) to explain the generative interplay of matter, movement, and mind. While MET is primarily concerned with molecular matter – flint, stone or clay – I will argue that this relational process translates just as well to the digital realm when combined with the phenomenology of technics, memory and affect of Stiegler.

Advancing the hylonoetic perspective in light of Simondon's theory of individuation would suggest that computational design does not arise from manipulation of mental plans and representations, but rather from within the complex interplay of forces in a given ecology reaching across material and informational domains. As noted by philosopher Shaun Gallagher (2014, 2017) this relational transaction is key to enactivism and brings about the creative and flexible projection of mind into our material, social and symbolic surroundings. I advance the concept of *enactive individuation* to describe this dynamic and non-representational process while seeking to bridge the concepts of grammatization, ephiphylogenetic memory, and hylonoetic field. The term seeks to capture how mind is crucially dependent on continuous enacting of hylonoetic fields that integrate technics, memory, and affect – and how mind and form are emergent properties of this activity and inherently tied to the specific fields being enacted. Technics and grammatization plays a crucial role in enabling and constraining these processes by acting as essential conduits for individuation over time (Stiegler 2013:34) while also framing moment-to-moment affective exploration and discovery of the specific opportunities of a given hylonoetic field (cf. Malafouris 2014:145). The creation of form through digital design research requires an understanding of how computational systems 'as form and as mathematical ordering constructs' operate. Following the relational framework advanced here, this understanding is embodied, practical and historical; it is made possible by the establishment of a technical milieu in which individuation can occur simultaneously in designer and system. Enactive individuation seeks to capture this domain of possibilities and the fluid and shifting processes of individuation across it while advancing a framework for analysing the explorative and open-ended entwining of mind with any technical environment – molecular or informational. The key notion is of a relational concept of agency and becoming; neither property of humans, nor of technics, but emergent from their enactive combination. As illustrated in the case below, creative agency and imagination only makes sense in this interactive, and affective, relational domain where all elements have had their power to deeply influence each other restored.

5 Design for robotic fabrication

The concepts of hylonoetic fields and enactive individuation provides a framework for analysing the effects of digital grammatization on computational thought and practice across a temporal scales. As already mentioned, the theory and practice of computational design questions relations between designer, technics, form and information while engaging a similar territory to the one outlined by Stiegler, Simondon, and Malafouris. Therefore, a further analysis of the robotic fabrication project advanced in the introduction might help clarify how the concepts of enactive individuation, hylonoetic field, grammatization and epiphylogenetic memory come together in computational design thinking.

5.1 Grammatization: Constructing the design model

The R&D project pioneers the use of robotics to cut moulds for advanced concrete formwork into EPS blocks (Søndergaard et al. 2016). It integrates the complexities of robotic fabrication into a digital 3D design environment with real time feedback allowing designers a better understanding of the impact of design decisions on actual cut surfaces. This computational integration is driven by the fact that the properties of a bendable and heated metal blade can be described and controlled numerically via the mathematics of *Euler elastica*. Euler elastica is the shape assumed by an elastic rod – such as a metal blade – when pressure is applied to its endpoints while its tangents are being controlled; knowing the material, the resulting shape is describable as mathematical functions of the pressure and tangents applied (Brander et al. 2016). By automating control of the endpoints of the heated metal with two robots, while a third pushes a block of EPS through the curving blade, the team can effectively automate the fabrication of almost any curved surface.

The use of Euler elastica and robotic control code represents several instances of grammatization in the sense put forward by Stiegler. For one, the precise mathematics of elastica allow for grammatization of material movement in the metal blade; its shape not only becomes numerically describable but also, by linking with robots controlled by computer code, numerically controllable. Any shape of the blade can be achieved within a given set of boundary conditions. The boundary conditions describe a number of limits for possible geometries beyond which designs become error prone or impossible to realise using the robotic fabrication setup. For one, boundary conditions describe the range of curvature within which the particular elastica for the metal blade are precise and controllable; exceed this range by having too acute an angle for example and numerical control becomes imprecise. Boundary conditions also describe the 3D space within which the three robots in the setup can function and work together without errors such as collisions. And they describe certain design constraints emerging from the use of different geometric primitives for describing shapes in different 3D modellers and resulting limits to their rationalisation into elastic curves.

5.2 Relational agency: Creating designs

The idea of the R&D team is that the robotic setup should be able to cut any geometry in minutes using well-known modelling software. However, none of the popular 3D modelling environments in use today[7] use elastica to describe shapes and input curves and geometry has to be approximated to elastica with the closest possible fit to the original for the robots to be able to cut it. Sometimes original input and approximations are incredibly close; sometimes they are not, meaning that the approximation has real and varying impact on the final shape of designs. To meet this problem, the team rely on a bottom up process in which the geometric constraints of robotic fabrication are incorporated into the design process from the start by having this approximation run in real time as users manipulate geometry in the design environment. To develop this generative design paradigm, the team continuously create and test automated approximation workflows at workshops for both team members and external participants. The design environment and workflow provides any user with real time approximation of her design to fit the constraints of robotic fabrication as she drafts them. There are a number of algorithms and steps underlying this. Input geometry is transformed into a coherent data structure that not only describe the geometry but also fit it within a virtual structure of several EPS moulds on screen to determine and visualise cuts. Advanced mathematical algorithms approximate geometries to successive curves of Euler elastica that can be cut with high precision by the robotic setup. All this goes on in near real time, so that users can change shapes and curves in the design modeller with a few movements of a mouse while seeing these changes continuously fitted within the design constraints of the robotic fabrication setup. This allows the designer to iteratively explore ideas in an intuitive manner while computations running underneath update the geometry. This real-time feedback invites fast interpolations from design to production ready geometry and ensures a smooth workflow from file to factory; rather than spending hours creating a full design and then checking if it fits within boundary conditions, which may lead to a lot of complex revisions, the generative design environment allows anyone to adjust designs on the fly through continuous feedback. In this way, the team not only ensure that designs fit within the boundary conditions of the fabrication setup, but the conditions themselves becomes generative of design.

Due to the grammatization of design constraints, that is their digital transformation to numerical information, the computational model can incorporate all of these while describing a step-by-step workflow for creating fabrication ready geometry using a normal 3D design modeller with an additional tool interface. Designers need no insight into robotics or the mathematics of elastica; all they have to concentrate on is manipulating the approximated geometries on their screens. Several years of research have been effectively grammatized and exteriorised for the everyday user, but remain active and accessible for users and software designers alike. In this way, the computational design environment works as a form of epiphylogentic memory, in the sense put forward by Stiegler, in that it actively stores, operationalises and manipulates the knowledge of the full project team. In effect, it is not just the dynamics of the metal blade or the movements of the robots that have been grammatized by the computational

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[7] The team use a number of programming environments and languages to create algorithmic tools and operations but integrate these into the 3D modeller *Rhino* using a parametric tool overlay called *Grasshopper*. The intuitive on-screen manipulation of geometry in *Rhino* is familiar to most architects today, and the open-ended nature of *Grasshopper* allow for effective integration of different tools, which can be easily accessed and manipulated by more adept digital designers.

model, but also the highly specialised knowledge of mathematicians, robotics engineers and architects.

An implicit claim from MET, is that we use material and conceptual tools to recast abstract problems into more meaningful and manipulable terms. At heart of the robotic fabrication project is a number of highly advanced material and numerical problems. The behaviour of metal blade and EPS foam. The description, control and limits of Euler elastica. The rationalisation of freeform curves into elastica. The data structure required for describing geometries in both 3D space and as numerical data. Interfacing with robot control code. To solve these problems in a way that allows non-experts to create designs that fit within the boundary conditions set by them, the R&D team had to recast problems from abstract mathematics and complex 3D movements of robots and blade into something more manageable. Something giving designers a handle on the constraints presented by robotic fabrication while allowing them to intuitively explore impacts of these along aesthetic lines. This is exactly what the computational model and workflow allow them to do, and I would argue that we could understand this modelling practice as a paradigm case of for advancing our understanding of enactive individuation and the hylonoetic perspective. Poulsgaard and Malafouris (2017) argue that the efficacy of computational models lies in their capacity to permit research into dynamic and complex systems at a humanly meaningful scale. This notion of complexity at a humanly meaningful scale offers a starting point for understanding the cognitive powers added by computational design models and can be further qualified by turning to the various temporal registers enfolded within modelling practice.

6 Temporality and affect in enactive individuation

The outlined workflow, permitting relatively intuitive design for robotic fabrication, is the result of more than five years of iterative R&D mixing insights from advanced mathematics, robotics and engineering, materials science, computer science, and architecture, with ongoing design research. The multi-layered temporality of this process is incorporated into the digital modelling environment, which links the full cycle of research, innovation, implementation and fabrication while creating a framework for geometric operations consistent with the robotic setup. The success of the modelling environment lies in the way it allows designers to selectively zoom in on, mix and process some aspects of this epiphylogenetic memory while completely ignoring others (cf. Cross 2006:37; Kallinikos 2005:189). Its practical development and use proceeds as a recursive series of enactive individuations across shifting temporal registers that connect design, technology and modelling environment with the affective experience of the individual designer.

6.1 Short term hylonoetic discovery

Due to the near instantaneous feedback cycles between input and approximated geometry, the generative design framework lends itself to explorative discovery not dissimilar to the creative process of pot-making put forward by Malafouris. Starting from an initial input, designers use their mouse to turn, scroll, drag and shape on-screen geometry to see approximated formwork unfold in front of them and through this come to discover the possibilities inherent in the modelling environment. When discussing this with architects involved in the project, they acknowledge an intuitive understanding for elastic approximation developing with time. This allows them to work at high speed and involvement with their designs, but the variable approximation of input to elastica means that design work takes the form of continuous exploration rather than straightforward hylomorphic transfer of preconceived form to the modelling environment. Watching architects play around with this tool it becomes clear that even highly symbolic and systematic art, such as computational design, relies on a very interactive and fluid engagement born from minute interactions rather than detailed master plans (cf. Suchman 2006; Yaneva 2009). Design work alternate between basic discovery involving periods of high activity with mouse and screen, continuously dragging and changing curvature to see what happens; these are interrupted by shorter periods for contemplation, where continuous movement and rotation of the on-screen block helps build a deeper understanding of the 3D impact of a given approximation. This in turn sets the designer up for more deliberate movements of curves. Sometimes these explorations go astray, the mathematical algorithms running the approximation returns uncuttable and loopy geometry and the designer undoes the past couple of steps with a few keystrokes to try again with a different approach. Alternatively, she incorporates the accident into her design; when discussing this with two of the architects, who helped develop and test this workflow, they both highlighted that there were geometries coming out of the workshops that could not have been made without the algorithmic approximation tools. As in the example of the potter at the wheel, the relational emergence of form and ideas materialise in ongoing transactions between designer, modelling environment, and interface, adding a digital dimension to the enactive analysis of MET. This explains how creative opportunities reveal themselves in computational design thinking through rich engagement within shifting hylonoteic fields combining an array of material and immaterial registers. The affective experience and history of the individual designer becomes key to making sense of this ongoing engagement.

6.2 Ongoing enactive individuation

The relationship between designer and tools in digital architecture is far from unproblematic and have received much critical attention. In particular, digital pioneers such as Mark Burry (2011b:116–17) have spoken out against theory and practice that cede creative agency of the designer to computational tools, either by blind copying and pasting of certain effects and algorithms or by uncritically embracing coincidence and accident as design strategies. Instead, he and others advocate for the skill and experience of the individual designer as digital craftsman to safeguard truly innovative architecture. This skill and experience relies on training and ongoing design research with both digital tools and molecular materials (Burry 2005, 2015); on the designer entering into a number of technical, informational and social milieus to creatively explore their potentiality. I began this article by citing architects Achim Menges and Sean Ahlquist (Menges and Ahlquist 2011) for highlighting an understanding of how systems, as form and as mathematical ordering constructs, operate as the underlying sensibility guiding computational design thinking. I hope the above case and preceding discussion of enactive individuation makes clear that this does not rely on decoupled symbolic manipulation but rather develops through engaging creatively with the emergent possibilities of informational and material worlds whose complexity mean that they are irreducible to purely mental representations and logics. Computational design thinking proceeds not only through rule-based exploration but also through sense-saturated transactions with other designers, design models, materials, interfaces, mouse, keyboards and screens within hylonoetic fields that reach across material and immaterial realms. The minutiae of these engagements should not fool us, the dexterity in manipulating onscreen geometry with mouse and code is akin to the embodied skill and dexterity of the pot-maker and is the result of an evolving practical history as much as any other craft (e.g. McCullough 1996; Barr 2006). The ongoing training, research and design work that makes this possible for the individual designer is analysable as ongoing processes of enactive individuation intimately joining designer with various social, informational and material milieus. Design theorist Nigel Cross (2006:102) has likened design thinking to the simultaneous exploration of unfolding problem-solution pairs. As design problems are seldom well-defined or bounded entities (cf. Rittel and Webber 1973), designers tend to understand the context of their work through series of solution conjectures that help them explore the problem formulation for specific projects; in this the problem and solution are intimately connected and co-evolve as context for design thinking. This analysis of problem-solution iteration functions well within Simondon's framework of individuation where individual (idea, design, designer) and milieu (workflow, R&D project, studio) emerge simultaneously from the operation of individuation; both partial and inextricable results of the creative interaction of bringing forth which Simondon calls the: 'procedure of the mind as it discovers'. In the robotics project, these procedures of discovery cover multiple timescales, from the minute feedback loops of geometric approximation on screen, to the longer R&D cycles leading to the grammatization of very different skillsets in the epiphylogenetic memory of the larger workflow.[8] The process is personal and affective; for Simondon, the creation of form, appears as an act of individuation arising from the need to resolve a tension, or potentiality, between a living being and its milieu (Combes 2013:27). There is thus a deep emotional investment in the process of individuation carried over in memories of this process which goes on to inform further individuations, or as Combes puts it: "*affectivity, the relational layer constituting the center of individuality, arises in us as a liaison between the relation of the individual to itself and its relation to the world.*" (ibid. 31).

6.3 Enactivism and affect across human, material and informational domains

Recent discussions in enactive mind highlight affective factors of embodiment and social interaction as key to a basic non-representational intentionality underlying cognition (Bower and Gallagher 2013; Gallagher and Bower 2014). In this perspective, affective contingencies – just as much as sensory-motor contingencies – shape our creative engagement with the world. These affective contingencies rely on acquired bodily and social experience and seem to support the learning of

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[8] One might even extend the timescale further back to the 300-year-old mathematical invention of Euler elastica, or to its predecessor in material computation of curvature in use since early Roman shipbuilding (Brander et al. 2016; Farin 2002).

skills by directing intentionality and enriching both everyday and skilled practice (Bower and Gallagher 2013:126). For digital designers, the everyday frustrations of working with the idiosyncratic instructions of code are well-known; "*if you don't know what that is then you don't know how lucky you are!*" as digital architecture pioneer John Frazer warns (Burry 2011b:52). Coders of all stripes incessantly discuss and obsess over programming languages, bugs and patches (Coleman 2013; Kelty 2008) and architectural R&D comes with its own specific hopes and anxieties as digital tools bring new creative potentials to the field (e.g. Ednie-Brown et al. 2013). Developing the robotic workflow discussed above is a non-trivial task relying on the successful integration of various fields still very much under development. This integration requires constant, meticulous (and creative) work as new improvements invariably introduce new problems threatening to halt the robots. At these times the frustration of the team members can become palpable. The memory of non-cooperative technology and exhilaration of successful trouble-shooting is a recurrent theme when they discuss current stages in the project and these experiences colour the expectations and excitement around present and future workshops. The nexus of technics, memory, and affect put forward by Stiegler seems to be alive and well in computational design research and active in shaping creative discovery and imagination. This emotional engagement further underscores a point central to Stiegler's work: a deep tension between promethean skill and stumbling inanity seemingly inherent in all creative technical work. Prosthetic being is existentially entwined with the ability to anticipate various futures for Stiegler, but anticipation is always faulty, introducing error and a deep uncertainty into the mix (Stiegler 1998:198). The computational workflow described here is efficacious because it supports cognitive processes that give designers an intuitive way to anticipate and work with the material and robotic behaviour inherent in the workflow, but this efficaciousness comes with a price which is an immediate uncertainty introduced by the complex contingencies of the system itself.

The bugs, and frustrations integral to computational design point to a potential for further bridging theories of enactivism and individuation by focusing on the role played by tension and affect in skilled practice. In combination, the enactive framework of mind put forward by Malafouris and the philosophy of technics and individuation from Stiegler and Simondon seems to suggest the outline of a theory, which I have tried to capture through the notion of *enactive individuation*. Enactive individuation seeks to describe how ongoing – affective – transactions between mind, materials, and informational logics extend imaginative capacities for computational design thinking. Through this non-representational but rich entanglement the affects of embodied practice come to shape aesthetic perception and imagination and the creative enactment of digital design research as ideas emerge and transform across human, material and informational domains.

7 Conclusion

The case of robotic design and fabrication has helped explore a number of issues outlined in the first parts of this paper. It has provided a case for comparison of computational design thinking to processes of *grammatization* and *individuation* thereby offering a phenomenologically anchored framework for understanding the logics driving digital design and fabrication. Specifically, it has shown how processes of grammatization allow for the incorporation of highly diverse material and immaterial registers into complex transactional ecologies anchored in computers and robots. The conceptual ideas worked out by a multidisciplinary design team, the bending of a metal blade, and the movements of robots, are all susceptible to grammatization using computational tools. For highly abstract mathematical entities, such as an automated syntax for robotic construction, a wide variety of material and conceptual registers integrate to allow for their purposeful manipulation into workable *hylonoetic fields*. The selective toggling between levels of complexity and abstraction inherent in 3D models and graphical user interfaces allow for functional simplification of these elements, giving designers the means for controlling exceedingly complex systems at a humanly meaningful scale. The case further allows us to address the question of a cognitive framework to underpin Stiegler's phenomenology of technical grammatization and individuation. Stiegler's notion of grammatization and epiphylogenetic memory relies on processes of exteriorisation and interiorisation but he does not describe exactly how these processes seem to work, nor which theories of mind might underlie them. I have argued that the affective and historical frameworks of MET and enactivism can help explain how these processes become efficacious through ongoing sense-saturated exploration. This has allowed me to compare computational design thinking to a recursive process of *enactive individuation* giving designers and design teams the transformative experience required for working productively with the vastly open-ended environments and problems inherent in digital design and fabrication. Design research is a mode of materially and bodily anchored thought in action, and becomes recursive – for both individual designers and the design community at large – in the way it is vitally engaged with extending the possibilities for this as a cognitive process. It is this transactional engagement that gives rise to original insights and imaginative ideas in computational design thinking. Creativity arises from the many possibilities within these hylonoetic fields, and enactive individuation and sense-making through embodied practice becomes a key activity for exploring the possibilities and constraints of new computational environments.

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