Digital materiality: creativity and collaboration in digital design at 3XN Architects and GXN Innovation

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Abstract

This thesis is about digital design at the Copenhagen based architecture studio 3XN Architects and GXN Innovation. In it, I examine how digital tools saturate design practices at the studio to develop a framework for analysing how design software and studio institutions come to shape architects' creative and collaborative work. The concept of digital materiality analyses the way successive layers of mathematics, code, and software come to mediate and shape creativity and collaboration for architects. I explore this through 15 months of ethnographic fieldwork at the studio where I interned and worked from 2017-2019. Taking the starting point that architects think with and through their social and technical environments, I argue that the organisation of these environments profoundly impact their creative capacity. The ethnographic side of this argument follows several design and research projects in the studio to analyse how social organisation and technics combine to enable creative and social extension of mind in design teams. I find that computational tools allow for intuitive creation of advanced 3D geometries. They integrate the mathematics and numerical calculations that underlie these into digital models that expand from being technical tools to also becoming vital design platforms at 3XN Architects and GXN Innovation. There is a certain flexibility to digital models and workflows in the studio. This flexibility is created from the combination of several software into one connected platform that can integrate the many moving parts of architectural practice and projects. This technical flexibility finds its parallel in the social organisation of the studio where different institutionalised practices allow architects to think about the same project in diverse ways, shifting between them by shifting relationships in their digital models. The wider theoretical contribution of the thesis examines productive overlaps between anthropological theory and enactive philosophy of mind by asking how these overlaps can help us study creativity as fundamentally enacted within shifting technical and social environments.

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Section I – Situation

Anthropology has engaged deeply and imaginatively with our relationship to technology since the founding of the discipline - and with our digitising lives from the 1990s onwards (see Pfaffenberger 1992, Coleman 2010 for overviews). Approaches are many and varied, here I follow a train of thought that seeks to situate people within their social, technical, and material contexts to understand technology as a relation between people, materials, and environments (e.g. Sigaut 2002, Hutchins 1995a, Suchman 1987). At its core this is an argument for holism and against methodological individualism as it refuses to seek out subjective explanations for phenomena, I believe are fundamentally relational. Our relationships with other people form the inescapable horizons for our lives – and as I will argue, these relationships inextricably entwine with technology (see also Stiegler 1998).

I devise the concept of *digital materiality* to analyse the way successive layers of mathematics, code, and digital interfaces come to mediate architect's creative work with computers and the possibilities of collaboration afforded them by software. The concept engages with current discussions in philosophy of mind, positing that mind is inherently situated, enactive and social – that we think with and through the environments, things, and people around us. I will argue that architect's relationships with computers, and the social organisations they give rise to in the studio, form an inescapable horizon for their creative and social extension of mind; and that the study of digital design in architecture serves a privileged place to explore the potential richness of our relationships with digital technologies more widely. By combining insights and approaches from anthropology and philosophy of mind I hope to shed new light on digitally mediated creativity and collaboration. The concept of digital materiality is an analytical tool to do so. It is developed, as is this thesis, out of 15 months of participant observation at the Copenhagen based studio of 3XN Architects and GXN Innovation.

The thesis consists of three sections with three chapters in each, as well as a final and concluding chapter. This first section situates the study within specific subfields of anthropology, specifically the study of creativity and studio spaces, the study of technology and material culture, and a growing body of work considering the social and situated nature of mind. I also discuss the site of 3XN Architects and GXN Innovation, as well as my methods of fieldwork. In Section II, I discuss technologies and practices of digital design to develop the analytical concept of digital materiality. In Section III, I discuss collaboration and social mind in the architecture studio and how socio-technical practices are mediated by digital materiality.

Chapters 1-3

Here, I situate the thesis across three chapters, introducing focus and fields of study, describing the site of study, and the methods applied.

Chapter 1: Introduction, situates the thesis within an anthropological tradition of writing against methodological individualism, and outlines its fields of study: the sites and situations of design, technology and architecture, and collaboration in architectural design. I describe my theoretical approach drawing on Material Engagement Theory and cultural theory, and outline the overall argument and structure of the thesis.

Chapter 2: Site, presents the studio of 3XN Architects and GXN Innovation where I carried out my fieldwork. In this chapter, I discuss the relationship between the two companies, their focus and financial and creative concerns, as well as how the work carried out here relate to the globalised field of contemporary architecture.

Chapter 3: Methods, discusses methods and my ethnographic fieldwork at 3XN Architects and GXN Innovation, including questions of access and my own role as a researcher hired by the company I was researching. The chapter discusses how the methods of ethnography have been employed in this specific setting and relates these to wider epistemological discussions in anthropology.

Chapter 1: Introduction

This is a study of creativity and collaboration at the Copenhagen-based architecture studio 3XN Architects and GXN Innovation (3XN and GXN). In it, I examine how digital tools enable architectural research and design at the studio, and how design practice, institutions and technology come to form a rich environment for the creative extension of mind. I seek to capture this environment through the concept of *digital materiality*.

Digital materiality describes the way successive layers of mathematics, code, and software come to mediate and shape creativity and collaboration in digital design. Computational tools saturate practice at the studio of 3XN and GXN. They let designers build intricate digital models, where geometry translates to data, and data to geometry. This shared informational basis permits functional integration across a wide range of software environments allowing for modular manipulation, combination and re-use of inputs and outputs from digital models across all phases of architectural design.

But while they share an origin in the realm of digital zeroes and ones, different design software uses different underlying mathematics to describe and transform geometry, they have their own structures for data management, and their controls and user interfaces support some ways of working over others. Most design software allow for creation of digital models and scripts where geometry translates to data and data to geometry, but due to their configuration they differ in the way they structure creative thinking and collaboration for architects. This depends on the way these models and scripts are made, the software used in their creation, their collaborative refinement over time, the skill of the teams whose work they integrate, and their evolving contexts of use in the design studio.

I develop the framework of digital materiality to analyse how these dependencies between software and social organisation interweave to shape architects' creative practices over timescales

ranging from minute interactions in front of screens to the long development of architecture and research projects. Throughout these timescales, digital materiality sees the correlation of human-technology as an inseparable part of our being in the world, and seeks to capture how the different configurations of software come to shape this being at a fundamental level. The wider theoretical contribution is an identification of productive overlaps between anthropological theory and enactive concepts of mind, asking how recent work in philosophy of mind can help us study creativity as fundamentally situated within shifting technical and social environments.

1.1 Digital materiality

I approach the concept of digital materiality with a kind of "instrumental realism," (Ihde 1993:3) taking the correlate between people and technology as fundamental to our being in the world. I ague that digital technology in a very real sense forms the horizon of architects imagination and collaborative practice in the studio (see also Stiegler 1998). This argument draws on an anthropological tradition of research against methodological individualism, which sees people as fundamentally relational beings (e.g. Marriott 1976, Bateson 1987[1972], Douglas 1986, Strathern 1988, Rayner 1992, Ihde 1993, Hutchins 2010). This relational view informs my ethnographic study of creativity and collaboration in the studio, it is central to my approach to technology, and it has led me to engage with a growing body of work in anthropology and philosophy considering the social nature of mind. Consequently, throughout the thesis, I seek to develop digital materiality as an analytical framework for understanding how design software and social organisation interact to shape architect's creative extension of mind. This framework is grounded in productive overlaps between anthropological theory and enactive concepts of mind. The shared starting point for these approaches is the notion that people are inseparably situated within their environments.

Digital Materiality against methodological individualism

Inquiring into the relations between collaboration, technology, and mind in architecture, this thesis takes aim at a series of deep-rooted dualisms in western thought. These dualisms postulate essential gaps between the individual and the world around. The most obvious is perhaps Descartes distinction between mind and matter, but from this follows a series of related dualisms such as mind/body, experience/nature, action/context, and individual/society (see Bateson 1987[1972]:343-4). In Architecture these dualisms have had their own technical corollaries in separate pairs such as thinking/doing, designing/building, and echoes of them can be found in later distinctions between digital and material (Picon 2010, Carpo 2011, Buchli 2016).

These dualisms encourage a subjectivist turn to the analysis of creative practice. If mind and body, experience and nature or individual and society are fundamentally distinct, the study of architectural design can quickly come to put primacy on the mind of the individual. This is methodological individualism, the notion that we must explain social phenomena through the aggregation of individual actions, which in turn must be explained with reference to the intentional states that motivate individuals (Douglas 1986). This methodological individualism is often accompanied by a specific kind of cognitivism that sees thought as computation or information processing happening within the confines of the individual brain[1] (Menary 2010).

Take a quick glance around the studio of 3XN and GXN, and it becomes obvious that these forms of individualism do not hold in contemporary architectural practice. The architects dart to and from conference rooms for project meetings, client presentations, and video conferences. They gather around team-based *pin-ups*, the hanging of printed materials showing the results of design research during projects. They cluster around screens to discuss digital models and renders. They

[1] Philosopher Gilbert Ryle (1949) criticised cognitivism and the idea that brain bound thought precedes actions by arguing that this lead to an infinite regress of thoughts preceding thoughts preceding thoughts. Ryle argued that intelligence was embodied, in action, and defined by culture, behaviour, language, and symbols.

show groups of clients around the studio or move in groups to examine the physical models that adorn the space. They cluster around the coffee machine at nine in the morning. They circle past each-others' desks to catch up on weekend activities. Every day at noon, they eat lunch together in the canteen.

The studio is an intensely collaborative environment. Teamwork, meetings, quick exchanges, impromptu huddles and a myriad of other planned and unplanned interactions are part and parcel of architectural design (see also Heath and Luff 2000:165-178, Yaneva 2009b, Houdart and Minato 2009, Parme 2018). And these interactions are in turn intensely digital. Digital tools and social interactions are inseparable at the studio. Two 24" LED flat screen monitors stand on each of the 120 or so desks at the studio, hooked up to computers with powerful graphics cards. On these screens 3D design software is used to create and keep track of shared digital models allowing teams to work together on architectural forms, elements, and details. Digital models are integral to collaborative work at the studio. They form the basis for concept design during competitions, construction detailing during project development, tool development in research projects, and 3D renders and virtual reality views for communication. In this environment, the question that comes to mind is not 'how can the creative work of these individuals ever be integrated into a coherent whole?', but rather 'how does this technical and collaborative environment produce creative work?' Or more prosaically: 'how does 3XN think and do architecture?'

Attacks on Cartesian dualism and methodological individualism has been part and parcel of anthropology for a long time. In his seminal book *The Gift*, Marcel Mauss (2016[1925]) argued that the mutual obligations of gift giving occurred between groups, not individuals, and discussed how objects, people, and institutions where inextricably mixed together in the process. Mary Douglas (1984[1966], 2003[1973], 1986) showed how intricate networks of classification form an

inescapable horizon for individual action, and how this constructed horizon is inscribed as naturalised fact or religious order through everyday practices. Gregory Bateson (1958[1936], 1972) placed man squarely within his social and natural environments through continuous engagement with concepts of ecology, information, and mind. And he developed and applied these to problems in anthropology, cybernetics, psychology, biology, and environmentalism – often while playing a formative role in these fields. In human-computer interaction, Lucy Suchman (1987) has advanced the notion of situated action to describe how people's embodied engagement with computers come to coproduce meaningful sociomaterial worlds. Following Douglas, Steve Rayner (1986, 1992) has shown how competing institutional dynamics within large organisations fundamentally shape people's possibilities for thought and action. Taking up the mantle from Bateson, Edward Hutchins (1995a, 2010, 2014) has examined notions of distributed cognition to understand how human mind is embedded within social and technical environments. Diverse as they are, these perspectives share the basic conviction that taken apart from their environment the individual is a pure abstraction.

This conviction leads to a focus on relations. Relations between people, and between people and environments, materials, objects, and technology. These relations are continuously created as people engage with their surroundings. Situated exchanges co-produce both individuals and environments, and the continued creation, contestation, and re-creation of these relationships come to saturate them with meaning[2]. Douglas (Douglas and Isherwood 1996[1979]:43) asked how people come together to create meaning from the inchoate flux of events that surround them. I seek to answer this question from the vantage point of 3XN and GXN by describing how architects continuously produce a rich environment of materials, technologies, interactional patterns and institutions in the studio. This environment is what I seek to capture with the concept of digital

[2] See Dewey's (2005[1934], 1999[1925]) notion of experience as the ongoing flow of interactions between individual and environments, and Harold Garfinkel's (1984[1967]) ethnomethodology arguing empirically that social interactions come to be part and parcel of the context at hand (see also Suchman 1987).

materiality. In it, digital modelling becomes an act of social creation as much as a vehicle for information processing. Continually engaging with and producing digital materiality, architects become active creators of meaning; this active exchange forms the basis of mind in the studio, which therefore is inherently creative, relational, and social.

1.2 Field of study

With the concept of digital materiality, I argue that architectural design cannot be separated from its technical and social environment. This places my study within a growing field of research on situated design practices, as well as longer running anthropological concerns with technology and collaborative work.

Situations of design

Anthropologist Ignacio Farías and sociologist Alex Wilkie (2015), published the collected volume *Studio Studies: Operations, Topologies & Displacements* in a bid to draw up the contours of this field of study. They define studios as coordinated work environments organised to support creative practice in fields as diverse as design, architecture, computer game development, and glassblowing. By moving beyond the enclosing walls of these spaces they seek to open the black boxes of creative production. Their programme shares a focus with earlier work in laboratory studies on knowledge in the making (see Latour and Woolgar 1979), but Farías and Wilkie (2015:9) point out that where laboratories are designed to provide new answers to well-defined problems, studio work consist to a large extent in finding and defining problems in the first place[3].

[3] This distinction between the studio and laboratory is too clear cut. Wicked problems and abductive reasoning are hallmarks in the theory of design thinking (see Cross 2006, Dorst 2011), but are also to be found in the laboratory and within theoretical science (see Achinstein 2001:17).

The volume offers diverse studies of creative practice, arguing that these are socially and materially distributed within studios and across studios and other sites of production. These studies have comparatively little to say about the materiality of the tools and objects created in the studio, however, and technology remains black boxed across the volume's chapters. I echo central arguments from *Studio Studies* about the relationality of design practice but also seek to extend this argument through the study of digital materiality, creativity and social mind, in architecture.

There have been a number of prolonged ethnographic studies of high-profile architecture studios. From 2002 to 2004, sociologist Albena Yaneva (2009a, 2009b) was a participant observer at Rem Koolhaas' Office of Metropolitan Architecture (OMA). Yaneva highlighted the contingent nature of design. She attended to the minutiae of day to day work at the OMA studio to argue that there exists a relative detachment of architects from the grand claims usually made for their finished projects (2009b). This means that day to day design work is focused on creative problem solving rather than grand narratives about society or creativity. In this work, Yaneva focuses on the creation of physical scale models. Detaching the study of architectural practice from the bread and circuses of starchitecture, vanity projects and the cult-like status awarded a few individual architects, allows Yaneva to study studio practices inventively and interestingly. Digital technology, however, is as good as absent from this study barring a few references to the software AutoCAD.

Anthropologist Sophie Houdart (Houdart and Minato 2009) spent eight months of observation at the Japanese offices of Kengo Kuma & Associates in 2003. Houdart was offered generous access to the processes of creation at the office and write an engaging first person narrative of her interactions with Kuma, his principals, and the young architects and model builders who seemingly work around the clock to realise designs at the studio. What emerges through Houdart's observations is another highly physical practice focused on model making. In 2008, Houdart visited the newly opened French office of Kengo Kuma & Associates. Here she found architects engaging digital

tools to realise an especially complex design strategy (Houdart and Minato 2009:157-164). She outlines the painstaking work required to coax the desired design language from the software, and touch upon problems of data-management and software incompatibilities but does not discuss digital tools in any further detail. Their configuration and how this comes to shape creative and collaborative work, which is a key element in the analysis of digital materiality, is not discussed.

Yaneva and Houdart show the range of influences in contemporary architectural design. They show the many shifts and turns projects go through in their development and detail the hours of work put in by architects seeking to create and concretise designs. Their situated perspectives pay less heed to the studio contexts of design, however. Their ethnographies focus specifically on the making of physical models but touch little upon how this is made possible in the first place. The detached focus on creativity in the making means that we hear little about the organisation of OMA and Kengo Kuma & Associates. While we gain a fascinating insight into studio principals' thoughts about architecture and their practice, we hear less about how work becomes meaningful to junior architects at the studio, how they learn the craft of design, and how this relates to their tools. Digital technology is either absent (Yaneva) or awarded relatively little space (Houdart) in these ethnographies focusing on the material practices of model making.

Touching on meaning and institutions, the architect Shira de Bourbon Parme (2018) spent eight months working with two leading urban planning offices in London during 2015-2016. Her ethnography follows the making of a large physical urban planning model, as well as planning drawings and reports. Participating in this production, Parme consider the performative role of materials and objects in planning practices. She highlights how socio-material arrangements in the studio allow architects to mix diverse uncertainties, such as zoning and client reactions, into their practice while using physical models to structure working relationships. Her study is particularly insightful on how planners use the creation of physical models and materials to work with, rather

than against, uncertainty. Parme explores how physical modelling allows architects to shift perceptions of time and space within the context of the studio (see also Rayner 1982). These shifts shape conditions for collective practice and help manage the uncertainties inevitable to urban planning. In this perspective planning becomes defined by a combination of material practices and social dynamics within the studio. I seek to extend this argument by focusing on how digital tools and social organisation interact at the studio to form a collaborative environment for architects.

On digital design technology, anthropologist Wendy Gunn (2002) has looked at the social impacts of incorporating Computer-Aided Design (CAD) into architectural practice. Gunn spent four months at Snøhetta, a leading Norwegian architecture studio, and carried out interviews with architects, historians, anthropologists and philosophers during 1997-1999. She found that CAD was incorporated into studio work as a means of reinforcing traditional practices around creation and management of project drawings. For her informants, software was seen as an optimisation and efficiency tool with little suggested bearing on the creative practices of design. This points to a tension between the sensorially rich work of traditional design practice when compared to digital design tools that challenge the embodied skills of Snøhetta's architects. Gunn is one of the few anthropologists to deal comprehensively with CAD technologies in architecture, but in her work computers emerge mainly as a challenge to the authenticity of material practice; the cold efficiency of the computer displacing the embodied sensibility of the designer and builder (e.g. Gunn 2002:33). Conversely I seek to capture the richness of digital practice and how this richness facilitates creative and collaborative work at 3XN and GXN.

Ethnographies of architectural design have very little to say about the creative potential of digital design software. It is as if the stigma surrounding CAD tools felt by Gunn – that these relate to engineering and optimisation problems rather than creative practice – still holds in the

anthropological study of architecture studios. Software is either absent (Yaneva 2009a, 2009b), taken as a back-drop to more materially engaged activities (Houdart and Minato 2009) or framed as extensions of embodied practices of drawing and building (Gunn 2002). In these framings digital design seemingly falls short of other practices when it comes to creativity and authenticity.

Anthropologist Victor Buchli (2016) has dealt with problems of digital materiality and immateriality and their shifting relations to authenticity. He argues that there is often a higher level of prestige attached to perceived 'immaterial' practices, including design, and takes care to note that immateriality is always materially produced. What Buchli attacks here are echoes of Cartesian dualism that sets the intellectual endeavour of design apart from its environments and tools. Along with the digitally minded architects at 3XN and GXN, I argue for the authenticity, richness, and creative potential of digital design software. Computational design introduce of new set of logics into design processes that set them apart from drawing and physical modelling. This is linked to the very materiality of software (see Ch. 5). Rather than perceive digital design as efficient (but uninteresting) extensions of existing practices, we should pay attention to how architects engage digital tools creatively to build upon the opportunities that different software provide. This is integrally tied to the configuration of software, and therefore the study of creative practice in architecture also entails the study of digital materiality, and how technology is developed and deployed collaboratively in the studio.

Technology and design

'Technology is a bastard child of uncertain parentage,' writes historian Eric Schatzberg (2018:14) and points out that shifting meanings of the word obscures our understanding of both the processes and results of technical activity. We do well to heed this warning, technology is a deceptively simple concept with a host of slippery meanings (Marx 2010, Schatzberg 2018, Coupaye 2009,

Sigaut 2002). Historian Leo Marx (2010) argue that these slippery meanings has made technology an all-pervasive concept today, but also a concept that is highly susceptible to reification. Too often, Marx writes, technology is consigned to the realm of physical objects, which obscures the social, economic, and political relations that are inherent in its development and use. Just as we argued against methodological individualism, we can argue against what we might call 'technological objectification' by saying that taken apart from these relations, technology remains an abstraction.

Etymologically speaking this is not far from the truth. The word technology fuses the Greek root *tekhne*, which means art or craft, with *logos* which means discourse or branch of learning. 'Technology is to technics what linguistics is to language, what every science is or would be to its objects,' writes anthropologist François Sigaut (2002:424). In this sense the word technology denotes the study of technical practices and products, yet this is clearly not our everyday use of the word. As warned by Ihde (1993), we often tend use the word to describe machines, gadgets, and things, but taken in isolation these can only be abstractions.

Both Sigaut and Ihde suggests that we cannot view technology in isolation, as abstracted tools, but should rather see it in relation to specific embodied practices that reproduce social institutions. Technology must be understood not as objects but as series of unfolding human-technology relationships embedded within each other. Ihde uses the word 'technoculture' to describe these relationships, arguing that technology embodies essential aspects of the culture of their production and use (Ihde 1993:57). Technology, in short, is anthropology – in the broadest sense of the word – and therefore fully integral to what it means to be a human amongst others in the world.

To avoid confusion, I use the word 'technics' to describe the tools of digital design, its software, scripts, and models, and 'practice' to describe the embodied ways in which people engage with these technics. I consider 'technology' as a larger set of technics and collaborative practices that humans use to transform the world around them in meaningful ways. Technics and practice are

material engagements with the world that we can know by the change they effect in both people and their surroundings. They emerge as social goals take the form of material needs (Sigaut 2002:424) and crystallise in shared objects, expertise, and knowledge. This means that technology is inseparable from culture as argued by Ihde (1993).

Technics are embedded in social situations of use, practice involves human creativity, and both presume meaningful engagement with a much larger world than what might be considered traditionally technical. As anthropologist Bryan Pfaffenberger (1992:498) argues in an overview of the anthropology of technology: 'A successful technological innovation occurs only when all the elements of the system, the social as well as the technological, have been modified so that they work together effectively.' (see also Gille 1986)

My concept of digital materiality seeks to capture these relationships by showing how the configuration of software facilitates specific forms of creative collaboration. My study shows how digital tools and collaborative practice are inextricably linked in the studio of 3XN and GXN. It emphasises social institutions in its analysis of technology and seeks to collapse distinctions between 'the individual' and 'the technical' to argue that mind is social and tied up with technics. There is nothing deterministic in the inevitability of this relationship. As anthropologists such as Sigaut (2002:446), Ihde (1993), and Pfaffenberger (1992) have taken care to highlight, the sheer complexity of human-technology relations introduces an inherent plurality of meaning into them. As our engagement with tools (tekhne) is embedded within larger organisational, social, and cultural mores (logos), plurality and variability are not accidental features of these relationships but essential to them. Plurality and variability is therefore also inherent in the very structure of creative collaboration via technology, which can only proceed through social definition of the meaning of both tools and the objects and environments they engender.

Mind in this perspective becomes enactive and social, inextricably tied to socio-technical environments (see also Ihde and Malafouris 2019, Aydin et al. 2019, Poulsgaard and Malafouris forthcoming). Perception, writes Ihde (1993:87) must always 'learn its ways', so it is for mind in digital design (see Section II), and this learning is a social process facilitated be technics (see Section III).

For contemporary architectural design, this means that, we can understand digital software and models as technologies that are inextricably bound up with practice and institutions in the studio environment. Like any technology, these models encompass organisational, social and cultural mores and therefore lend themselves to variability and ongoing creative discovery. This socio-technical coproduction is integral to the studio of 3XN and GXN. Its architects develop digital models, scripts, and workflows to enable meaningful creative work across studio departments, and between the studio and its many collaborators and clients. By enquiring into these relationships through the lens of digital materiality, we can begin to understand the inseparable entanglement of human mind with technics, practice, and social organisation.

Architects themselves have made extensive studies of digital design and the relationship between technics and technique in digital architecture (e.g. Lynn 1993, Aranda and Lasch 2006, Hight and Perry 2006, Gramazio and Kohler 2008, Burry 2011b, Banke 2013). As the field of digital architecture is establishing itself, a number of critical voices have emerged from within its own ranks, vitally engaging with its theory and practice (Kolarevic 2003, Terzidis 2006, Oxman 2008, Picon 2010 Burry 2011b, Menges & Ahlquist 2011, Carpo 2011, Davis 2013b, Oxman 2017, Rowe 2017). A basic assumption for these discussions is that designers are facing a new terrain in design thinking and that there is a need to formulate a rationale for digital design theory and practice (Oxman 2008:102).

Architects Achim Menges and Sean Ahlquist (2011) have advanced the notion of *computational design thinking* to describe this new field. They discuss the inextricable relationship between the systems of computational design, its software and models, and the procedures and reasoning required by architects to work with these systems. The position of the architect is changing, argues Menges and Ahlquist, as computation relies on the purposeful establishment and execution of rules for the development of forms, but not explicit descriptions of final forms themselves. For some, this shift from finished object to process, from free-form design to rule-based exploration, is at the heart of digital design (e.g. Lynn 1993, Schumacher 2008). But as Buchli has pointed out the notion that digitised design modelling suggest an 'objectless' world of pure code obscures the different material registers of the digital (Buchli 2016:145, see also Blanchette 2011). Within Menges and Ahlquist's procedural definition of digital design it also remains unclear exactly how imagination and creativity emerge in interaction with digital tools, and how this interaction is situated within the larger context of the architecture studio. The vanguard of digital architecture describe the technics and techniques of their field engagingly but tell us less about how computational design is made meaningful as a technology (see Burry 2011b for a notable exception).

On meaning, Suchman's (1987, 2006, 2011) seminal work in Human-Computer Interaction (HCI) helped shift the study of our engagement with computers away from cognitivist models of search and information processing towards the situated creation of meaning[4]. Her work shows how technics (in this case photocopiers) is inseparable from technique (embodied ways of using them), and how our interactions with technics come to reflexively constitute their meaning. She advanced an ecological approach to HCI where the key point of analysis is the interplay between 'plans' and 'situated' action at the machine interface. Plans, in Suchman's work, represent the explicit and imaginative formulation of a procedure of actions (e.g. the steps required to operate a 1980s

[4] See also philosopher Hubert Dreyfus' (1992[1972]) and computer scientists Terry Winograd and Fernando Flores (1986) influential critiques of overly cognitivist approaches to computers and cognition.

photocopier), while situated action represents practical on-the-fly reasoning (whatever we do once plans break down or stop being effective). Her work shows how plans are constantly reconfigured and adapted to the contingencies of actual interaction with technics. Extending this situated perspective to the study of digital technology in design, Suchman (2011:7) has argued that computers are 'physically embodied and contextually embedded, such that their abilities and limitations depend on a physical substrate and a surrounding situation.'

In attending to the technics of digital architecture, procedural steps and formal knowledge of how these systems operate can only tell part of the story. This part is indisputable, and too often it is missing from anthropological studies of design activity, where digital technology is either down-played or black-boxed. But to avoid abstraction, the study of technics and technique must be situated within the shifting social contexts of the design studio where it is developed and contested in creative practice. In the words of anthropologist Ludovic Coupaye (2009:94): 'objects do not emerge fully clad with their properties before being injected in the different sets of transactions they are integrated into.' The meaning and use of technics is reflexively constituted in social practice. This highlights the rich field of 'cosmologies, constitutions, and civics' (Healey and Rayner 2009:33) shaping the enactment of specific technologies, in the wide sense described above. And this turns the study of creativity and technology in the design studio towards the study of organisation and collaboration.

Collaboration in design

The practice and epistemology of design has been widely theorised from the 1960s onwards. Early work on the science of design had roots in artificial intelligence and combined approaches from cognitive science, computer science, engineering, and information theory (Newell et al. 1959, Alexander 1964, Simon 1996[1969], Simon and Newell 1971). This approach was developed within

a cognitivist paradigm and highlighted problem solving through search and information processing. Later work highlighted the explorative and contextual nature of design practice, linking reflective reasoning with the open-ended problems of design (Schön 1983, Cross, 1982, Rowe 1982, 1987, Buchanan 1992, Lawson 1994). During the 1990s changes to the administrative structure of design education in the UK, led practitioners and academics to argue for the value of design as a research field in its own right (Frayling 1994, Archer 1995). Later studies of design processes draw on this varied heritage to discuss how studio based and problem-oriented knowledge is generated and shared in ways that set design research apart from other research practices (see Dorst 2011).

These approaches have established the disciplinary foundation for design studies, but have comparatively little to say about technical and collaborative aspects of design work. Architect and design researcher Rivka Oxman (2017:7) argue that: 'Prominent among the large body of research in design thinking are observations related to personal introspective thinking in sketch-based media.' While studies of technics and technique in digital architecture have introduced a focus on digital practices into the study of design thinking (e.g. Menges & Ahlquist 2011, Oxman 2017, Rowe 2018), the collaborative aspects of digital design work remain underserved. Sociologists Christian Heath and Paul Luff (2000:7) has warned that:

> Contemporary sociological research concerned with technology seems in various ways to separate systems, both technical and human, from social action, so that we are unable to recover just how tools and artefacts and the "rest of the furniture" of the modern organisation is constituted in and through the activities of the participants themselves.

Heath and Luff both draw on, and define themselves against, the research field Computer Supported Cooperative Work (CSCW). They welcome a focus on cooperation and technology, but also warn that conceptions of technics and organisational behaviour often are quite rudimentary in CSCW (ibid. 14). Focusing on 'the work that makes technology work.' (ibid. 30), their own study of architects and CAD highlights the growing complexity of architectural design, and how new

technology necessitates the distribution of activities and responsibilities in the architecture studio. Heath and Luff discuss how a substantial part of architectural work happens in front of computers. They show that individuals' actions with computers unfold in close interaction with others, while the screen becomes a new resource for collective work (ibid. 176-177), but there is little discussion of how the computer is used as a tool for creative production of ideas and concepts.

Educational researchers Jonas Ivarsson, Gustav Lymer, and Oskar Lindwall have been utilising ethnomethodology and conversational analysis to investigate studio based teaching and technology in architecture (Lymer et al. 2009, Ivarsson 2010). They show how minute interactions structure the flow information and the nature of collective decision-making in front of screens in architecture education. The interactional patterns discussed by Heath, Luff, Ivarsson, Lymer and Lindwall, clearly show that technics and collaboration interweave at the microscale across practice and teaching in architecture. Their studies outlines how gestures, shifts in orientation, and pacing in the architects' interactions utilise the technical environment, and how this interweaving of social and technical resources come to be part of unfolding design situations. But this hyper-situated perspective tells us little about how the action relates to larger organisational realities surrounding these situations, or how structures and learning form one situation spill over into and come to inform the next. In short, how people and organisations learn and work at the macro-scale. With the concept of digital materiality I seek to bridge between the rich minutiae of situated technical engagement and the macroscale of studio organisation and learning.

Hutchins (1995b, 1995a) study of the ways in which social interaction and technics entwine in the cockpit of a plane, or on the deck of a large US Naval Ship, illustrate the power of these minute interactions on larger scales. The concept of distributed cognition is central to Hutchins' work on navigation and air-traffic control. Working with pilots, Hutchins analyses the cockpit as a cognitive system in its own right by tracing the ways humans and tools interact to create 'representational

states' supporting certain actions over others (Hutchins 1995b, Klausen and Hutchins 1996). When pilots fiddle with their dials and controls they actively produce and maintain simplified representations of a much more complex underlying reality and thus cognition in these systems is not happening in the minds of individuals but relies on the propagation of representational informational states in the cockpit as a whole. Hutchins follows the trajectories of these modified representations of information such as speed, weight and altitude, through the technical and social engagements of pilots to explain how the cockpit as a cognitive system remembers its speed at various points in flight. The technical layout of cockpits as well as the distribution of labour between pilots and air traffic control become durable cognitive artefacts that pilots use. These artefacts are not separate aide memoires as their effects emerge through specific interactions between pilots and their surroundings. These interactions are the tip of an iceberg of tacit and embodied knowledge about flight plans, speeds and loads (Klausen and Hutchins 1996), and the interactions are inscribed in several overlapping mediums of memory – standardised procedural chains, instruments, tables, divisions of labour – giving rise to embodied routine actions.

Hutchins work shows that the cognitive properties of groups can be different from the cognitive properties of the individuals in them, and that this difference is stabilised through organisational routines and material culture (Hutchins 2010, 2005). He has advanced the concept of cognitive ecology to describe this (2010). This concept is central to my analysis of how technics and social interaction interweave in digital architectural modelling, and come to enable creative practice and social mind at larger temporal scales. But Hutchins' examples are drawn from contexts that are too hierarchical and rigid when compared to the studio of 3XN and GXN. You do not want your pilots to get overly creative *en route* to Luton; on the other hand, I suspect that clients paying for architectural work would not be satisfied with their commissioned architects slavishly following routine to reproduce the same building over and over again.

1.3 Creative and social mind

To examine creative practices at the studio of 3XN and GXN, I develop digital materiality as a framework for analysing how design software and organisational institutions come to shape architects' digital work. This framework is grounded in productive overlaps between anthropology and enactive concepts of mind.

Material Engagement Theory

In his 2013 book, *How Things Shape The Mind*, cognitive archaeologist Lambros Malafouris provides a comprehensive reframing of the problems of cognition and creativity by situating them within a relational framework of mind and material engagement. Here creative thought becomes a situated activity where mind emerges through dynamic interaction between a variety of embodied, material and cultural domains. This situated perspective does away with Cartesian dualism by refusing to locate mind either in the head or in the world. Rather it seeks to overcome these and the other dualisms (mind/body, experience/nature, action/context) by showing how elements usually posited on either side of these pairs are entangled in ongoing processes of mind in action.

Material Engagement Theory (MET) uses our rich engagement with material culture to explain how creative thought is inextricably tied up with action (Malafouris 2013, 2014, 2015, Ihde and Malafouris 2019). In this perspective mind becomes co-extensive with technics and matter (Poulsgaard and Malafouris 2017, forthcoming). Mind is an emergent and enacted process, and we have to do away with notions of the brain as either originator or primary location for thought and action. Neither bound by the head nor the body, mind emerges from interactional ecologies reaching well beyond the individual (Malafouris 2013:37, Poulsgaard 2019). What matters is the coextensive entwining of cognitive processes, technics, materials and culture in situated and embodied action. The key epistemological and practical problem for MET becomes accounting for

the ways in which different material registers come to co-constitute and extend the plastic flexibility of mind. And a key problem for the application of MET in this thesis becomes accounting for how aspects of the digital world such as mathematics, code, software and interfaces come to constitute its own materiality with very real impacts on creativity and collaboration at in the studio of 3XN and GXN.

Enactivism and material agency

MET positions itself against cognitivist theories of mind. These theories share a fundamental reliance on representation as they argue that cognition proceeds through series of manipulations of mental representations of reality. This reproduces a dualism between internal representations and the external world, mind and matter, thought and action (Ryle 1949). In cognitivist theories of design, creativity becomes synonymous with mental manipulation of representations of a given problem with little interference from the outside world – whether material, technical, or social (see Newell et al. 1959, Simon and Newell 1971). This theory of creativity is too limiting for a comprehensive analysis of digital design practices as it leaves little scope for understanding the interplay between architects and digital tools in the specific institutional contexts of the 3XN and GXN studio. Cognitivism also risks actively obscuring the role played by processes inherent to the tools themselves by locating the creative action solely within the minds of architects.

Against cognitivism, MET champions a relational approach to thinking and doing. Creativity and mind emerge through an interplay of forces extending beyond individuals into environment, culture, tools and materials. This perspective radicalises theories of extended mind (Clark and Chalmers 1998, Clark 2010) by collapsing distinctions between internal and external elements of cognition. This follows recent work in the field of enactivist philosophy of mind that propose to move beyond theories of extended mind by rejecting representations, while recasting the bounds of cognition;

deprived of representations mind becomes enactive, essentially world involving, inherently extensive rather than occasionally extended[5] (Varela, Thompson and Rosch 1991, Thompson 2007, Di Paolo 2009, Hutto & Myin 2013, Gallagher 2014, 2017, Hutto, Kirchhoff & Myin 2014, Rietveld & Brouwers 2016, Kiverstein & Rietveld 2018, Bruineberg & Rietveld 2019). MET shares the anti-representationalism of enactivism by recognising that embodied material engagement acts as a fundamental cognitive resource in its own right – that we think with and through things in action. What matters in this perspective are neither internal representations nor their mental manipulation but rather how material engagement helps us cast difficult problems into more manageable terms that support imaginative solutions.

MET proposes to move beyond mental representations by developing a concept of the material sign which opens for analysis of *enactive signification* (Malafouris 2013:99). Material signs do not primarily embody a representational logic but an enactive one. They anchor and instantiate meaning through their very materiality; they stand for something, in ways that symbols cannot. Malafouris cites Bateson to the effect that:

> The lions in Trafalgar Square could have been eagles or bulldogs and still have carried the same (or similar) messages about empire and about the cultural premises of nineteenth-century England. And yet, how different might their message have been had they been made of wood! (Bateson in Malafouris 2013:91)

The difference that makes a difference reaches beyond the symbolic realm. For Malafouris material signs are actual physical forces that shape the social and cognitive universe. This depends on a strong commitment to enactivism, where situated and embodied action brings forth the terms

[5] These approaches can be grouped under the banner of '4E cognition' which posits that mind is embodied, embedded, enacted and extended, and if nothing else share a common enemy in mental representations (Menary 2010). While the field has been incredibly productive, there are only few examples of 4E cognition taking on the challenge of digitally extended mind (Clark 2003, Edmonson & Beale 2008, Alač 2011, Clowes 2015). Here I wish to show how enactive and embodied cognition can encompass digital practices through the concept of digital materiality, which I develop as a framework for understanding how digital tools transform creative mind (see also Poulsgaard 2019).

of interaction[6], including the material sign, design problems, tools, models, and ideas. Enactive signification highlights how creativity and mind rides on movement, affect and transaction with shifting materials, and how this transaction profoundly shapes perception and imagination for cognitive agents (see also Gallagher 2014).

This commitment to interactivity has consequences for our concept of agency in design. In MET's enactive perspective design action does not primarily arise from mental plans and representations, but rather from within the interplay of forces in a given relational ecology (see also Rietveld 2016, Rietveld & Brouwers 2016, Bruineberg et al. 2018). Agency becomes an emergent property that cannot be reduced to human or non-human components. It becomes the property of an interactive, relational domain where all elements have had their power to influence each other restored. The notion of *material agency* seeks to capture this domain of possibilities and the fluid properties of mind in action across these (Malafouris 2013:147). Enactive signification and material agency are at the core of digital materiality: when analysing processes of digital design, we can neither reduce our explanations to the creative genius of the individual designer nor to the cold hard logics of computational tools; rather we should see how design intent and experience flow together in situated material interaction.

MET develops a framework for applying the theory of enactive mind across a variety of time-scales from here and now interaction to human evolution. This commitment to processes unfolding at various timescales presents a dynamic framework for analysing design research within its broader institutional context. We humans have plastic minds enfolded within plastic culture, and constantly stabilise and alter process of mind through creation of cognitive ecologies (Malafouris 2014, Hutchins 2010, Bruineberg and Rietveld 2019). The main thrust of this is the recognition that the

[6] This relational perspective shares fundamental tenets with Harold Garfinkel's ethnomethodology which sought to show the enacted nature of background knowledge in routine and everyday scenes. Garfinkel's experiments in breaching social expectations and decorum questioned the common-sense view that background assumptions are part of our mental states prior to action (Garfinkel 1984[1967], Suchman 2006:67).

crux of human cognitive evolution: ‘is not to be found in the ever-increasing sophistication or specialization of a modular mind, but in an ever-increasing projective flexibility that allows for environmentally and culturally derived changes in the structure and the functional architecture of the brain's circuitry.’ (Malafouris 2013:46) By interacting with technics and materials we change the projective flexibility of our minds. Crucially, these interactions also co-produce cultural institutions, that are socially grounded, shared, and contested (Gallagher 2013).

Cultural theory

In anthropology, Mary Douglas was among the first to explicitly state the question of mind in social terms. Her 1986 book *How Institutions Think* showed a deep concern with breaking away from ill-fitting individualistic or cognitivist explanations for thought and action. In her own words, Douglas sought to develop a theory of institutions that could amend contemporary ‘un-sociological’ views of human cognition, as well as: ‘a cognitive theory to supplement the weakness of institutional analysis’ (Douglas 1986:ix). While she succeeded in the first move by drawing on a wealth of anthropological evidence against simplified notions of rational choice and individual self-interest, the latter remains underdeveloped. With MET and enactivist approaches to cognition we can shed new light on the theories of social cognition underpinning Douglas’ work while bridging material, technical and social worlds.

With *How Institutions Think* Mary Douglas developed arguments from *Purity and Danger* (1984[1966]) and *Natural Symbols* (2003[1970]) by putting socially shared institutions at the heart of cultural theory (Douglas 1986:ix). For Douglas, sanction of social order explains how institutions emerge, the cognitive load they remove from individuals navigating a world in flux, why they persist (Douglas 1986:48). Drawing on the legacies of the French sociological tradition and English functionalist anthropology, Douglas advanced a theory where socially constructed and shared

beliefs about society provides templates for consciousness in the form of functional classifications, logical frameworks, analogies and guiding metaphors provided to the individual by shared institutions. This 'sociology of classificatory analogies' (Kearle 1988:208) is deployed to explain the emergence and durability of social institutions protecting the collective good. In this sense institutions not only shape mind, but also come to embody and direct everyday action – often in quite a comprehensive way.

'Institutions have the pathetic megalomania of the computer whose whole vision of the world is its own program,' writes Douglas (1986:92), and just as we today increasingly find ourselves having to navigate the informational logics of computers, we also navigate the classificatory logics and moral codes inherent in shared institutions. From this emerges the elementary pieces of a cognitive theory reaching beyond the individual to show how day-to-day thinking relies on socially shared behaviours for making sense of the world and structuring thought and action. In light of MET, we can begin to ask how institution are enacted in everyday material practice and how they come to form part of technical design processes. We should be aware that institutions are inherently and efficaciously tied to technics, materials, protocols and paperwork. Institutions need not be singular, static or all-pervasive. As we grow increasingly interconnected, we have seen institutions multiply, become fragmentary, contradictory and fluid while not diminishing in affective salience (Appadurai 1996).

Rayner has developed a dynamic approach to cultural theory through analyses of collective sense-making across professional and technical environments (e.g. Rayner 1984, 1991, 1992, 2012, Healey and Rayner 2008, Patel and Rayner 2012). He argues for the existence of plural rationalities within organisations and a framework that takes into account how people switch between meaningful practices dependent on the social contexts they find themselves in (e.g. Rayner 1986, 1992, Rayner and Malone 2001). This highlights a fluid mode of social interaction where

individuals knowingly and unknowingly shift between institutional registers to further their arguments and add meaning to their behaviour. This opportune and contingent navigation is a close cousin to the situated perspective of enactivism and MET.

Social mind: creativity and collaboration

Writing about enactivism and social cognition, philosopher Hanne De Jaegher and computer scientist Ezequiel Di Paolo (2007) analyse the practices we employ in everyday interactions. They show how social sensemaking is an enactive process contingent on shifting interactional patterns rather than overly formulaic cultural norms. For them, sensemaking is inherently relational and very much in the moment[7]. It is tied to embodied action in social interaction and produces (or fails to produce) meaningful encounters.

Alongside cultural theory, this focus on enactive sensemaking adds a distinctively social perspective to the analysis of mind. De Jaegher and Di Paolo opens for a greater understanding of the inherent flexibility in social situations, as highlighted by Rayner, by adding awareness of how a variety of social affordances come to shape extension of mind.

The concept of *affordances* was first forwarded by ecological psychologist James J. Gibson (1986). Affordances are possibilities for action provided to us by our environment, by the materials, technics, objects, and people that surround us (Chemero 2003). In the relational perspective of digital materiality, these affordances can be seen as actual relations between people and environments as these are made and remade in situated practices.

[7] Though a priori dispositions can play a great part in coordinating everyday interactions, focusing on predispositions alone risk obscuring the capacities of situated interaction in the meeting (De Jaegher & Di Paolo 2007:11). De Jaegher and Di Paolo bring in Bourdieu's work on habitus and recognise the fact that the stuff of table manners and greetings are grounded in shared norms, but insist that these only make up so much of what goes on in participatory sense-making. This grounded perspective shares overlaps with Suchman's (2006[1987]) focus on 'plans and situated actions'.

Philosopher Eric Rietveld and colleagues have extended the standard concept of affordances to encompass a 'rich landscape' of interacting material, social, and cultural factors (Rietveld and Kiverstein 2014). They have done so by paying ethnographic attention to the complex interplay between architects, sketches, software and models in design situations (Rietveld and Brouwers 2016). This work brings together philosophical reflection and ethnography to emphasise the role played by discovery and learning in our ability to engage meaningfully with affordances. To analyse how this works, they advance the concepts of *skilled intentionality* and *optimal grip*.

Skilled intentionality is defined as the intentional coordination between several, sometimes competing, affordances in a given situation (Rietveld 2016, Bruineberg and Rieveld 2019). Rietveld shows how this works from within the architecture studio by discussing how designers simultaneously interact with software, sketches, and other people by directing attention towards salient aspects of these (while ignoring others) through intense creative engagements (Rietveld and Brouwers 2016).

Optimal grip entails reducing tension in situations of skilled activity through interactions that seek to bring aspects of the competing affordances into alignment with specific goals such as evaluating sketches, discovering a better design, or advancing the situation of design itself (Rietveld and Brouwers 2016). This does not require knowledge about an optimal alignment of affordances, but rather entails embodied engagement with the situation through practices that help move the architect from a state of tension towards, if not harmony, then at least reduction of tension. Skilled intentionality therefore entails tending towards an optimal grip on a design situation by being selectively responsive to multiple simultaneously available affordances (Bruineberg and Rietveld 2019, Rietveld and Brouwers 2016).

How digital design tools and models form part of these rich design situations is what I seek to analyse with the concept of digital materiality. Crucially for this, Rietveld shows how social

learning and discovery are key to architects' ability to engage meaningfully with these manifolds and how the social experience of individuals therefore come to inform extension of mind in design. The enactive approach of Rietveld, Di Paolo, De Jaegher, and others thereby adds a phenomenological and affective dimension to the concept of affordances by paying attention to how people's experience extend across multiple situations of interaction always shaping their possibilities for creative engagement with the affordances of new situations.

The institutional perspective of cultural theory highlights how experience with and some degree of conformity to socially shared norms become prerequisite for skilled interaction with others within extended landscapes of social, technical, and material affordances. The enactive focus on social mind shows how these institutions are constantly negotiated, made and remade in situated practices involving rich landscapes of materials, technics, and people. This will be discussed in more details in chapters on design research (Ch. 6) and design interactions (Ch. 7).

Philosopher Shaun Gallagher (2013) has developed theories of social affordances, institutions, and cognition further to show how socially extended mind can reach beyond the immediate affordances of situated interactions between people to also rely on institutional structures, norms and practices. In line with this we should conceptualise institutions as socially coordinated and materially supported behaviours that fundamentally change peoples' cognitive systems. What matters is the properties and affordances in the emergent cognitive system as a whole. Institutions themselves are transitory but can maintain identity over time by actively bringing people materials and symbols in line with their programmes. This relates to the enactivist view of affordances and material engagement forwarded by Malafouris and others; a key element of enactive mind, whether this relates to simple experiences of space and time or complex systems of social mores and material culture, is the implicit creation of correspondences between domains of experience, blending embodied, material and symbolic inputs (Malafouris 2013:100, Rietveld and Brouwers

2016, Bruinberg & Rietveld 2019). This not only explains how social institutions find a rich multimodal domain to tap into, but also how they take on highly charged meaning and a life of their own through a rich web of symbolic variations and material culture. And it explains how these multimodal institutions actively shape cognition by offering a rich relational field for minds to extend through (Gallagher 2013).

Ideas about social mind have some traction in anthropology (e.g. Bateson 1987[1972], Douglas 1986, Hutchins 1995a, 2010, Pina-Cabral 2017). This thesis seeks to develop these approaches by investigating how architects co-create relative stability out of the inchoate flux of events that surround them, and how this stability is constantly and creatively contested, manipulated and re-imagined in collective practice. I seek to take up materialist strands within these approaches (e.g. Douglas and Isherwood 1996[1979], Hutchins 2005, Malafouris 2013), by advancing the concept of digital materiality to analyse how social organisation, technics and materiality co-produce possibilities for creative and social mind at the studio of 3XN and GXN.

I argue that social, embodied, and enactive conceptions of mind allow for better understanding of digital practice by advancing relational and dynamic frameworks for analysing how people engage with their environments. Showing how these interactions emerge and change across situated and distributed practice is a core concern for anthropology. Bringing together enactive and institutional perspectives on collective mind highlights the richness of specific situations as key to understanding human creative practice. These focus areas are well-fitted to ethnography, and to develop the analytical framework of digital materiality, I engage with ethnographic examples from my work with 3XN and GXN. These examples allow for further exploration of how anthropology and enactive approaches to cognition might productively be combined in the study of digital practice;

they do so by bringing forth co-dependencies at the heart of architects' work with expanding the capacities of technics, meaning, and mind in the studio.

1.4 Structure of thesis

The thesis is divided into three sections of three chapters each, as well as a final concluding chapter. In each section, I will discuss specific questions from the study of modelling, materials, and mind in digital architecture.

Section I – Situation

The first section situates the thesis within specific subfields of anthropology, notably the study of creativity and studio spaces, the study of technology, and a growing body of work considering the social and situated nature of mind. I also discusses the site of 3XN and GXN, as well as my methods of study.

Ch. 1: Introduction

Chapter 1 introduces the main anthropological and theoretical concerns of the thesis. I outline the overall argument and structure of the thesis.

Ch. 2: Site

Chapter 2 presents 3XN Architects and GXN Innovation. I discuss the relationship between the two companies, their focus and financial and creative concerns, as well as how the work carried out here relate to the globalised field of contemporary architecture. Economic and cultural globalisation driven by intensifying networks of digital technology erode any naive notions of *field* and *site* as

overlapping entities out there to be discovered. The fact is that we as ethnographers create our fields in meetings between places, people, and a set of highly institutionalised practices of travelling, observing, and writing. I engage this discussion to situate my own creation of a site of study at the studio of 3XN and GXN.

Ch. 3: Methods

Chapter 3 discusses methods and my ethnographic fieldwork, including questions of access and my own role as a researcher hired by the company I was researching. I describe how I have deployed methods of ethnography to develop the concept of digital materiality and analyse extended and social mind in digital modelling practices at 3XN and GXN.

Section II – Technics

The second section will establish the concept of digital materiality to advance the analysis of the interplay between technics, materials, and institutions in design. It will discuss digital software and models in architecture in depth to describe how the construction and configurations of software come to vitally influence creative and collaborative extension of mind. Each chapter outlines a specific element of an interconnected technical environment shaping and being shaped by day-to-day practice at 3XN and GXN, these are *code*, *model*, and *screen*.

Ch. 4: Code

Chapter 4 discusses scripting and numerical representation of geometry. I advance the thesis of digital materiality by discussing computational design research at GXN, and examine how architects manipulate software, data, and code in their research work. Digital materiality describe how the mathematics and configuration of software enable certain creative practices over others

while enabling architects to manage geometric and formal complexity at a human meaningful scale. The discussion of digital materiality will begin to show how creative agency and mind is invariably distributed between architects and their software, models and scripts.

Ch. 5: Model

Chapter 5 examines how the digital materiality of different design software are brought together in digital models at the studio of 3XN and GXN. I discuss the model as a distributed platform that integrates a variety of practices and logics to discuss how different digital material registers shape process of mind in the context of architectural projects in the studio. I outline an instance on problem solving one such project to clarify how the 3XN and GXN modelling platform anchors cognitive ecologies in the studio. In anthropology, the notion of cognitive ecology argues that mind is essentially a distributed phenomenon. I will argue that the digital modelling platform is a vital element of cognitive ecology at 3XN and GXN, and that the architects' minds are extended and materially anchored in practical engagement with platform.

Ch. 6: Screen

Chapter 6 further elaborates on the computational modelling environment at 3XN and GXN by investigating screen-based design research. Work in front of screens is at once virtual and material, combining a seemingly endless array of possibilities with the substantial constraints of software, digital materiality, and the studio modelling platform. The chapter explores how architects situate themselves within this environment to establish a sense of scale that allow them turn the disorienting sleekness of computational design software into creative possibilities. I link notions of architectural design research to anthropological discussions of the embodiment of skill to argue that

digital design is embodied and historic, vitally dependent on the creative experience of the individual designer within the social context of the studio.

Section III – Collaboration

The third section outlines the influence of social organisation and institutions on mind in digital architecture. The chapters in this section discusses collaborative practices at 3XN and GXN and how patterns of collective behaviour relate to the pervasive use of digital models at the studio.

Ch. 7 Team

Chapter 7 will focus on the interactional patterns of design teams, to show how these patterns provide the opportunity for participatory sense-making, and the merging of different forms of expertise and knowledge. I will argue that situated collective practices become constitutive of social mind in design teams, and that the creative potential of these practices comes to rely on larger institutionalised patterns of behaviour, which provide a meaningful context for collective cognition.

Ch. 8 Project

Chapter 8 will expand the temporal scale of analysis by looking at the development of an architectural project from early competition phases to buildable designs. I will discuss how stabilised concepts are shared in and between teams during the project's lifetime. This discussion rests on a materialist version of the anthropological concept of dividuality where the exchange of scripts and models between architects come to facilitate larger scale patterns of participatory sense-making in projects.

Ch. 9 Studio

Chapter 9 will enquire into the wider studio context of the practices first described in Chapter 8. I seek to expand the temporal scale further by investigating how emergent meanings are stabilised in the organisation and practices of the 3XN and GXN studio. The argument relies on dynamic strands of cultural theory, inspired by Mary Douglas and further developed by Steve Rayner, to show how different ways of organising shared work shape architect's possibilities for thought and action.

Chapter 2: Site

This chapter presents the studio of 3XN Architects and GXN Innovation (3XN and GXN). The two companies are owned by the same holding company and share a studio space in Copenhagen's Holmen harbour. 3XN creates internationally renowned architecture in a Scandinavian tradition. Examples such as the new Headquarters for the International Olympic Committee in Lausanne and the high-profile CUBE Berlin office building set between the Berlin Hauptbahnhof and Reichstag feature in this thesis. GXN is an architectural research company and engage in collaborative projects in the fields of circular economy, digital design, and human-centred design.

In this chapter, I discuss the relationship between the two companies, their focus and financial and creative concerns, as well as how the work carried out here relate to a global field of contemporary architecture. To situate this discussion, and lay the foundation for the analysis that follows, I outline recent work in multi-sited and digital ethnography, and use this as starting point for elaborating how I constructed my own field of study during my time at 3XN and GXN.

2.1 Entanglements

The term 'field site' reveals a concern with the spatial delimitation of a research project harking back to anthropology's early days. In the beginning of 20th century, the ethnographer could satisfy himself (and his review board) by mapping out the social contingencies of a small region on the colonial map, a village, or patch of villages, which could be made to stand for a coherent and self-contained whole (Narayan 1993).

In the early 21st century, some notion of field and site remains necessary for the production of anthropological knowledge. Malinowski's call in *Argonauts of the Western Pacific* to imagine oneself: 'suddenly set down … alone on a tropical beach close to a native village,' still echo

through ethnography today, sometimes quite literally as in the opening lines of Tom Boellstoff's (2008:3) study of life within the online villages of Second Life. But the echo distorts, as increasingly research *fields* do not map smoothly onto spatially coherent or self-contained *sites*. If they ever did. In his 1921 foreword to *Argonauts* Malinowski (1922:xv) himself highlighted the 'ludicrous and tragic position' inherent in ethnographic field work, which sought to delimit local forms of native life that was rapidly changing under pressures of globalisation. It seems the acceleration of exchanges between people, technics, and information was already inducing professional anxiety a full century ago. Today it has become one of the central facts of contemporary life, and a core condition for anthropology (see Appadurai 1996, Gupta and Fergusson 1997, Tsing 2000).

Field site

Economic and cultural globalisation driven by intensifying digitisation erodes any simple notion of *field* and *site* as overlapping entities out there to be discovered by the intrepid researcher. Instead, globalisation has ushered in debates about the constructivism inherent in field work; the fact that we as ethnographers create our fields in meetings between people, places and a set of highly institutionalised practices of travelling, observing, and writing (Gupta and Fergusson 1997, Marcus 1995). Under this new paradigm, anthropologists were urged to cast away the limitations of any single site and instead follow the flows of globalisation, its supply chains, networks, and cultural refractions across sites (Appadurai 1996, Tsing 2000, Marcus 1995). George Marcus, who helped pioneer this line of thinking, points out that today's anthropologists have to: 'work through knowledge economies, global projects of political economy, assemblages, or circulations to find its way to both its traditional and new subjects at the ethnographic scale.' (Marcus 2013:200). Interestingly, this account borrows heavily from the language of architecture and design when

urging anthropologists to follow the 'vectors' of globalisation to uncovers its 'temporalities,' 'plans,' 'designs,' and 'technologies' (Marcus 2013:202, Ingold 2011, Rabinow et al. 2008).

Globalisation and technology certainly impact the world of architectural design. The work of 3XN and GXN functions within a globalised knowledge economy, where value is created through the circulation of ideas, narratives, and digital models as well as through the construction of buildings. The need to engage shifting opportunities in this knowledge economy in part accounts for the success of GXN, the research company, in the larger framework of 3XN the architecture business (see below). In simple terms, the practice of architecture today is at once situated in the design studio as a site of knowledge production, and distributed across global sites of economic surplus, knowledge production, and material construction.

How to approach the creation of a field of study from this particular tangle of material and virtual sites? Taking up the methodological glove thrown down by Marcus and others during the 1980s and 1990s, Jenna Burrell (2009, 2012) brings anthropological concerns with field and site to bear on the study of digital practices. Her research on youth and internet in Ghana is instructive for the way it adapts Marcus' (1995) notion of the field as a multi-sited network of physical, virtual, and imagined spaces. Across these spaces Burrell follows flows of people and information as they shape practice in the internet cafés of Accra. This allows her to trace social practices that are at once material and virtual, situated and globalised.

Following a similar line of reasoning Christine Hine (2015) has brought attention to how digital media, even though highly distributed are also embedded in local contexts that are both mundane and personal for the people using them.

I rely on a strategy of constructing a field of study from a defined spatial vantage point, while also following the flows of people, projects, and information extending from there into other sites.

In order to construct a field of study from these shifting flows and connections, Burrell advises that we attend to: 'the point of origin, the destination(s), the space between, and what moves or is carried along these paths is of interest.' (Burrell 2009:190)



Fig. 2.1 The studio of 3XN Architects and GXN Innovation in Copenhagen's Holmen harbour.

My point of origin is the studio space of 3XN and GXN in Copenhagen's Holmen harbour (fig 2.1). This was my entry point into the field of digital architecture and remains the site of my most intensive engagement with its practice. During 15 months of ethnographic work there, the studio became a vantage point from which to construct the wider field of study. This field was created by following people, materials, and information carried between destinations in and beyond the studio (fig 2.2).

The studio is organised into three overall departments: Competitions (3XN), where architects seek to land high-profile architecture projects through competition and commissioned design; Project Development (3XN), where architects and specialists advance designs to finished drawings for tender and construction; and Research (GXN), where architects develop strategies and tools for circular, digital, and human-centred design. My field of study grew from my desk at GXN. Stacks of papers, funding applications, print-outs, and reports accumulated on my table. Within a few weeks my own two screens filled up with documents, spreadsheets, presentations, temporary folders

and hastily sourced pictures, reports, notes. I began to move more easily in the office as projects developed, circulating from my own desk past the desks of Morten in Project Development and Kenn in Competitions after they generously started showing up at mine to chat about projects or whatever else were on their mind.



Fig. 2.2 Studio interior, 3XN Architects and GXN Innovation.

Morten and Kenn form the core of 3XN and GXN's Digital Design section. As I began helping them on projects, funding applications, and conference presentations, my field of study expanded to new destinations at workshops in Odense, Paris, New York, London, Darmstadt, and Copenhagen. This helped bring the preoccupations and concerns of the wider digital design community into sharper focus. Research projects on Circular Economy developed with Kasper, the founder of GXN and Lasse, the Head of Consultancy introduced me to a network of Danish and global project partners, and helped introduce a better understanding of the political economy of architecture and construction. Working on 3XN competition inputs for a Children's Hospital in Copenhagen and a primary school in the Copenhagen suburbs introduced a practical understanding of the organisation of teams between 3XN Architects and GXN Innovation. A case study of the digital modelling of the new IOC Headquarters designed and built by 3XN Architects in Lausanne brought the digital and virtual connections underlying this organisation to light.

I will go into these projects in more detail in the following chapters, but here wish to illustrate how, during the 15 months I worked at GXN, connections forged between these people, projects, and sites began to form a coherent but distributed field of study. This field was spatially distributed through the sites of design research and knowledge production mentioned above. It was socially distributed as it followed the architects through their different projects. And it was technically and virtually distributed as it followed the digital models and scripts which served to tie these separate sites together. The intensifying flows of people, technology, and information in architectural practice also influence day-to-day work at 3XN and GXN. To some extent, then, this thesis seeks to map a global geography of architectural design and research, but from the specific vantage point of 3XN and GXN. While I hope other architects and researchers can recognise the landmarks of this geography it will be highly specific and tied to my time in the Copenhagen studio.

2.2 GXN Innovation

I started fieldwork Monday August 8th 2016, when I began an internship with GXN Innovation in Copenhagen. My fieldnotes records this as an impatient day taken up with a studio meeting in the morning and periodically refreshing my email during the remainder of the day while wondering what I would be doing in the coming months. Around me, GXN was starting up after a two-week summer vacation where the studio had been closed. At a 9.00 am studio meeting, the five architects and four interns who then made up the GXN team introduced themselves and welcomed me with a few curious questions. In a relaxed atmosphere over cinnamon twirls and coffee they talked about upcoming projects and shared impressions from their summer vacations spent variously visiting family abroad, surfing in Portugal, or watching Tour de France from the couch.

I told everyone how excited I was to be there and tried to impress on them that anthropology meant participant observation, and that participation in day-to-day work was what I hoped to be doing. After the meeting, everybody settled into the projects they had waiting without paying me particular attention. Over the following days, I could record the account of my new workplace as told to me by its employees and read from the pages of the documents, presentations, and books I now had access to. In the presentation of 3XN and GXN below, I will share work I helped develop, run or contribute to, as well as a number of projects from the archives, to give an idea of the diversity of work going on at the studio. This will be presented without much analysis or comment to try to give the reader an idea about the site I entered in summer 2016 and its connection to a wider globalised field of practice in architectural design and research (More in depth studies of two key projects – the GXN research project Digital Factory and the 3XN architecture project for the IOC Headquarters – will be described in Sections II and III).

GXN Innovation was founded in 2007 by Kasper Guldager Jensen, then a partner with 3XN architects. His goal and agreement with 3XN was to launch GXN as an independent research company for applied design research into new technology and materials in architecture. GXN was, and still is, owned by 3XN Holding but have to maintain a balanced budget without cash injections from its parent. Doing this, while growing the company and its influence in the wider world of architectural research, remained a key concern for us while I worked there.

By the summer of 2018, the GXN team had grown to 18 people, ten architects, six interns, and two industrial PhDs. This meant, Kasper told me and Lasse at an impromptu budget meeting at his desk, that we had to maintain a DKK 666.000 (GBP 80.000) monthly turnover to keep in the black. Lasse would jokingly be referring to this as ‘the number of the beast’ over the following days.

Funding for GXN's work comes from research grants and consultancy fees. The combination of open-ended research projects, and more tightly defined consultancy tasks, allows GXN to do explorative experiments while also building up practical applications for state-of-the-art materials, technologies, and techniques. During my time at the studio, Lasse was responsible for developing consultancy projects, while I, graduating from my internship into a job after three months, became responsible for developing research projects. In practice, most people on the GXN team, myself included, worked across research and consultancy projects as it was a strategic goal that knowledge developed during research could be applied in consultancy services for clients such as developers, municipalities, and non-competing architecture offices (either significantly smaller in scale compared to 3XN or focused on different specialisations and markets).

During the 15 months, I was working at GXN, some of the consultancy projects included developing a circular construction strategy and product line for Peikko, a Finnish manufacturer of steel and concrete fittings; creating a sustainability and technology strategy for large Danish hospital; creating circular urban development tools for the City of Amsterdam; and developing mechanical and virtual prototypes for 3D printing and robotics with the Danish AM-Hub, a national accelerator for additive manufacturing in Denmark. I worked on all these projects and served as project manager for the latter two.

Across research and consultancy projects, GXN is loosely organised into three strategic sections: Behaviour Design, Circular Design and Digital Design. These sections coordinate research and practice in GXN and also structure how these interfaces with architecture and business strategy at 3XN. While I worked there, 3XN and GXN successfully won a number of projects by combining approaches while promising to deliver additional value through human-centred architectural solutions, circular construction principles, and digital design and project delivery. Accordingly,

GXN's Behaviour Design section is built up around the two companies' combined work with mapping and designing relationships between architecture and behaviour. The Circular Design section involves capacity building and design development for a circular economy in the built environment. And the Digital Design section focuses on developing the wider studio workflow and technical backbone, as well as on digital research projects in design, data, simulation, modelling, robotics, and fabrication. In each section, several specialists make up the core group. They build up their skills and experience from project to project, but most people come to work across all the sections as teams are set in an ad hoc fashion dependent on the requirements of individual projects.

During my time with GXN, projects were also increasingly beginning to combine approaches from the three sections. One example is the GXN run Designing Out Waste research studio with the Laboratory for Integrative Design at the University of Calgary (Forward et al. 2019), which explored applications of robotic fabrication techniques for circular economy; another is the development of research collaborations in sensing, data, and machine learning for understanding social behaviour in built environment. I helped develop both of these, though the latter remains unfunded.

As these brief examples and the case studies in the coming chapters will show, GXN's practice is necessarily collaborative and distributed: part of a situated and globalised knowledge economy as discussed by George Marcus (1995, 2013). This is as much the case for research projects as it is for design and consultancy. When my work began in earnest, Kasper told me that GXN research seeks to team up with global knowledgeable partners in academia and industry to find ways of applying their knowledge and products at the architectural scale.

In its 12 years of existence, GXN has participated in some 110 research projects. Some of these as a member of large EU Horizon 2020 consortia, including BioBuild (2012-2015), which

researched applications of bio-based materials in construction, and CIRCUIT (2019-2022) which will explore how to use design and digital tools to introduce Circular Economy into urban planning in five European cities. Together with Lasse, I developed the GXN contribution to the latter. Other collaborative research projects have smaller teams but run across longer timescales, such as the six-year Bladerunner (2012-2015) and Digital Factory (2015-2018) projects, developing robotic fabrication techniques to create moulds for curving concrete forms. Others are smaller in scale and scope such as the Learning From Nature Pavilion (2009), exhibiting parametric design and bio-based materials at the Louisiana Museum of Modern Art; an early success, which according to Kasper 'helped put GXN on the map'. Today, GXN is an internationally renowned research unit with projects and ties across Europe and Northern America and articles published about its approach in leading design journals and books (e.g. Henschel & Nilsson 2015, Burry and Burry 2016, de Rycke et al. 2018). The results of all this work litters the GXN space in the Copenhagen studio at Holmen. 3D printed and laser cut objects, material samples, parametrically designed objects, technical products, and mock-ups of tectonic principles sprawl across desks, shelves, and bookcases, giving the space a somewhat messy feel when compared to the relative order in the remainder of the studio.

The GXN material library sits in packed shelves in the middle of the space with samples of both high and low-tech molecular innovation. High-performing technical composites and bio-based samples are organised into sections based on their materiality. This includes wood, ceramics, insulation materials, glass, cork, plastics, bio-composites, photovoltaics and smart materials.

Examples of GXN's own participation in research projects are also present. A series of bio-board samples made from upcycled waste materials such as tomato stems, straw, and eelgrass; intricate lamps made from laser-cut vinyl plates coated with a kaleidoscopic reflective film; large doubly-curved polystyrene blocks, smoothly cut by automated robots.



Fig 2.3. Overlooking GXN and the material library.

A custom made stand showcased colourful packages of seeds made in collaboration with biologists to introduce native Danish plants from biotopes such as fens, salt marshes, and heaths into the built environment in an attempt to increase urban biodiversity (I spent a welcome afternoon away from the computer in the autumn of 2018, shovelling, digging and planting some of these biotopes outside the office at Holmen).

Amidst all the mock-ups, materials, and samples stand books and journals featuring GXN cases or articles on design research (Henschel & Nilsson 2015, Burry and Burry 2016, De Rycke et al. 2018), others published by GXN and partners following research or design projects (Jensen and Sommer 2018, Forward et al. 2019, Arup and Ellen MacArthur Foundation 2020), as well as published industrial PhD theses developed at 3XN and GXN on architecture and behaviour (Sylvest 2017), and simulation of solar radiation for parametric design (Banke 2013).

As I would come to realise while trying to map out the distributed practice of GXN during early field work (see Ch. 3), all these materials help render GXN's shifting constellations of people,

projects, and technologies visible after the fact. Much day-to-day work in GXN takes place in physical and virtual meetings all over Europe and North America, and on the dual computer screens sitting at each table. Whether people are modelling complex geometry, creating scripts and inputs for architectural projects, are designing technical mock-ups based on new materials or tectonic principles, create presentations for communicating ideas to project partners, or are writing concept notes, emails and budgets for project development, this virtual work remains hard to grasp for anyone not involved directly. Its various physical manifestations help make the contours of a field of practice evident (in the early days they certainly helped me get a grasp of my field of study). In some sense, materials, from digitally carved geometric forms to more ephemeral reports and printouts, become the visible tip of the iceberg for this practice and field of study. They become important for introducing potential partners to the day-to-day work done by GXN, and serve as references in the studio to remind new employees and 3XN architects about the wealth of connections and skills that make it possible[8]. This is important for the integration of collaboration in the studio, as well as for the wooing of new clients as we will see below.

2.3 3XN Architects

GXN's parent company 3XN Architects was founded in 1986 in Aarhus, Denmark by young architects Kim Herforth Nielsen, Lars Frank Nielsen, and Hans Peter Svendler Nielsen. They called their company 3xNielsen.

The three Nielsen's approach to architecture was inspired by Robert Venturi's (1966) postmodernism, which was preoccupied with the contingencies of particular briefs and sites rather

[8] As I discuss in Chapter 5, virtual models and digital scripts also serve as knowledge repositories for bringing together different specialist skillsets from within and beyond 3XN and GXN.

than advocating any particular visual style[9]. This preoccupation can be witnessed in early 3XN buildings such as the House of Architects in Copenhagen (completed 1996), situated at the harbourfront next to a 17th century dry dock and warehouse (fig. 2.4). The building balances historic references and contemporary styles while housing both the Danish Architects Association and the Danish Ministry of Foreign Affairs. The separate identity of the two organisations are marked out by distinct building elements, a floating concrete box volume on the eastern facade of the building and a full wooden façade on the western. Both are enveloped in a glass vitrine offering clear views of building materials and detailing to recall the site's historic and contemporary uses.

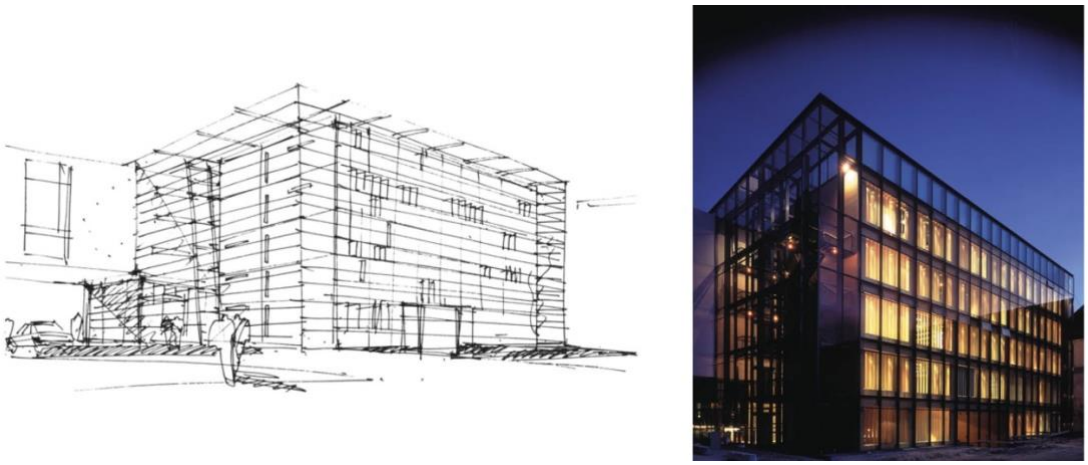

Fig. 2.4 The Architects House in Copenhagen. 3XN Architects 1996.

By the early 2000s Lars Frank Nielsen and Peter Svendler Nielsen had left the company to pursue careers in academia and design, and in 2010 Kim Herforth Nielsen moved the company from Aarhus to Copenhagen to focus on Copenhagen based projects and a growing international portfolio. Today, 3XN Architects is owned by 3XN Holding, which in turn is owned by the five senior partners: Founder and Creative Director Kim Herforth Nielsen, Head of Design Jan

[9] Critic Oliver Wainwright (2018) has argued that the architect Denise Scott Brown was 'one half of an equal creative and intellectual partnership' with Robert Venturi and had as much a hand in developing the postmodern approach. She was a respected teacher before marrying Venturi and has been overlooked for most of her career by a male-dominated field which shows a poor record of recognising contributions from female partners to better known male architects.

Ammundsen, CEO Jeanette Hansen, Director of GXN Kasper Guldager Jensen, and Senior Partner Audun Opdal. Eight partners were added to the leadership in 2015, which was further expanded in 2017 with its first non-architect partnership to Jack Rentiera, Head of Business Development.

This last appointment betrays the vital importance of business development for a studio which, while firmly rooted in its Danish context, increasingly look to international markets. This shift towards international markets was in part prompted by the financial crash of 2007-2008 and the prolonged slowdown which followed in Scandinavian and European markets. This connection between subprime mortgages, financial modelling, a globalising economy and localised construction markets show another sense in which work at the studio is inextricably entwined with and dependent on successfully navigating the vagaries of global knowledge economies.

Today, 3XN have smaller offices in Stockholm, Sydney, and New York connected to specific projects and strategic growth markets in these regions. The company continuously works with leading European, Australian, and North American property developers on some 20 architecture projects with collective construction costs of GBP 1,2 billion. For any architectural office, architectural projects entail teams of architects working on specific ideas, designs, and problems for years on end. In this way, projects come to profoundly influence both architects and studio (see Ch. 8 and 9). 3XN's global outlook developed during the 2000s with a number of prize-winning projects such as the Danish Embassy in Berlin (completed 1999), the Muziekgebouw Amsterdam (completed 2006) and the Liverpool Museum (completed 2011).

With these and similar projects, 3XN has become an internationally oriented studio, which proudly wears its Scandinavian roots on its sleeve (3XN Architects 2013). In a recent book on the state of Danish and global architecture (Weiss 2017), 3XN's work is profiled along with other internationally minded Scandinavian design studio's such as Bjarke Ingels Group, Snöhetta,

Henning Larsen Architects, and COBE. Kim Herforth Nielsen, is interviewed and repeats the maxim that *form follows function* to explain the 3XN approach to architecture with explicit reference to a Danish heritage counting Arne Jacobsen and Jørn Utzon. He elaborates on this approach:

> The classic virtues with their focus on composition, volume, proportions – let's just call them the Nordic tradition – are coupled with an element of storytelling, and that is the new space of possibilities we work in. … Telling stories with architecture is simply our way of understanding and imagining architecture. (Weiss 2017: 189-190).

As any anthropologist will tell you, storytelling serves to establish order by enshrining meaning in coherent narratives, while also seeking to naturalise this order by reference to nature, 'self-evident' truths, or transcendent powers (Douglas 1986). Of course, this goes for telling stories via architecture as much as via interviews. Kim's referencing of classic virtues, Nordic history, and the transcendent influence of Arne Jacobsen and Jørn Utzon serves to both elucidate a creative approach that is not tied to any particular style, while also legitimising a rising studio seeking to set itself apart in a competitive globalised economy (fig. 2.5).

The studio's contemporary practice integrates international ideas, new technologies, and young architects from most of the Western World as well as China and the Middle East to develop its particular take on design and research. To situate these flows, the studio maintains its historical commitment to the specificities of brief and site with a Scandinavian emphasis on how buildings come to shape the possibilities for social life within them.



Fig. 2.5 Render of Quay Quarter Tower with Utzon's Sydney Opera House visible in the far left corner. 3XN Architects under construction.

2.4 Studio departments

The 3XN Architects and GXN Innovation studio occupy a large wooden shack in the old Holmen harbour of Copenhagen. From the outside, the listed shack retains a traditional look of black-tarred wooden planks, white smallish windows and five red tiled gable roofs tilting across its five sections or 'ships'. The light and spacious interiors of the studio stand in contrast to the outside, and to me the space has always seemed considerably bigger from the inside than from outside. Exposed wooden structures carefully restored after a fire ravaged the building in 2006, light wooden surfaces, and a large number of integrated skylights creates a surprisingly light interior compared to the black-tarred exterior walls. The shack sits at a slight slant towards the water of the inner harbour channel and large floor to ceiling windows look out onto the channel, with the home-made houses of Christiania, Copenhagen's 'free city' rising from the reeds across the water. Behind the bastions of Christiania, the large silver furnaces of a new powerplant lend an industrial feel to the scene.



Fig. 2.6 3XN and GXN studio plan.

Inside, the studio space is more or less open. The five ships are organised into five open sections running the length of the shack (Fig 2.6). The southernmost (to the left in the plan above), houses the shared space where most people have lunch together every working day; the second houses five glass-enclosed meeting rooms, and towards the water, the studio space of GXN; the middle ship has the entrance and reception area and along with the next one houses Project Development; the final ship is home to the Competitions department and Model Workshop. Besides the large wooden beams making out the core structure of the shack and meeting rooms dividing the canteen from the

rest of the studio, the space is open allowing you to look from one side to the other. Everybody, from senior partners to interns, sits in this open space at the same grey tables. The space is filled with large architectural models from the model workshop. Realised and unrealised projects clutter shelves and table tops around the studio and walls are hung with white foam models from projects.

Some 100 architects, interns, designers and business developers work at 3XN in this studio, and 18 architects, researchers and interns at GXN. Most are of these people are young, somewhere in their late twenties, as both offices take in a considerable group of international master's students and young architects right out of school. These are overseen by more experienced project architects, studio partners, and senior partners. The 100 + 18 architects occupying the studio of 3XN and GXN are preoccupied with winning competitions, problem-solving during design development and construction, collaborative research, and ongoing communication and business development. Looking though the studio at any given day, they are preoccupied in meeting rooms or in front of their screens, creating and manipulating 3D geometry, developing construction detailing, sending data packages from models to service project partners, finding and solving construction errors, analysing project costs, and managing the business of architecture.

The people working at 3XN are organised into four departments: Competitions, the Model Workshop, Project Development, Business Development, with GXN making up the fifth: Research.

Competitions department

The Competition department's core business is advancing aesthetic, striking, and functional design concepts in answer to project briefs. For this reason, not just competition proposals, but also all 3XN commissions, and some GXN research projects with a strong design angle, have their vision

and content worked over by designers from the Competition department. Architectural competitions sees teams of architects and experts from inside and outside of the studio work to deliver striking and functional answers to design briefs. They can last anywhere from two to 12 weeks, usually somewhere in the middle of this, and come with a limited predefined budget that must pay for all personnel hours and overheads.

Architectural competitions stipulate a range of requirements to detailing, plans, sections, views and renders, and on larger projects also models, which must be turned in, but there are seldom upper limits to the production value of the materials. Relatively low fees alongside high production demands, means that 3XN's response to competitions have to be tightly managed affairs focused on achieving a high turnover of ideas, concepts, and visualisations in short time frames.

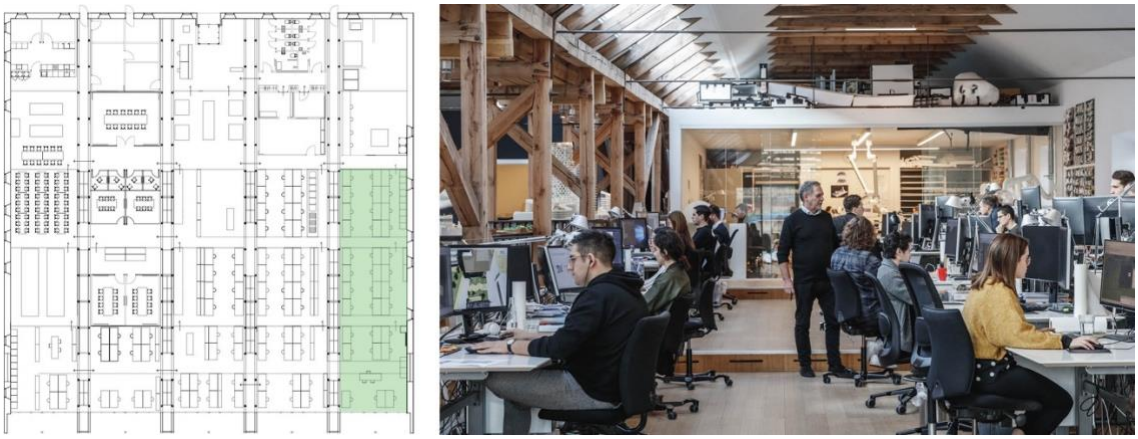

Fig 2.7 3XN Competition Department.

Competition work involves concept design and sketching, volume studies to understand the spatial relationships of brief and programme, design research and form finding, façade design, and quite often a series of more or less detailed physical models in foam, wood, plastic and 3D printed materials. All this work is carried out in design software, usually Rhino and Grasshopper[10], and as the project matures is integrated into a central digital 3D model. Increasingly early stage design

[10] The specifics of design software utilised in the studio of 3XN and GXN will be discussed in Chapter 5.

work incorporates simulations of sun, wind, and rainfall to refine the performance of the finished building, and this information is integrated into the digital model as well. Views and high-definition 3D renders (and sometimes 360 virtual reality views) are also produced from this model.

Some 30 designers work in the Competition department on teams comprising anything from two to ten (or more) people dependent on the project. The teams are usually organised under a partner, and mix experienced, early stage, and intern architects. All competition architects that I spoke with told me that good ideas can come from anybody in the team, and that these are usually refined collectively. The teams sit together. They will cluster together on an ad hoc basis in front of each other's screens to discuss ideas or problems, and meet ongoingly to study the materials and models produced for the competition. These materials are hung up around the competition department for everyone to see. The teams are highly integrated, work is judged collectively and with rolling deadlines, but the partner responsible for the competition team, and/or the Creative Director and the Head of Design has the final word.

Model workshop

Model building remains integral to the practice of 3XN Architects. Models of buildings, volumes, or detailing are integral to understanding the spatial relationships of a design, which according to several competition architects can be difficult to tease out from the virtual views of digital models on screen. High-end, carefully made, models are also used to communicate designs to clients and are handed in for high-profile competitions.

The model workshop creates all of these models in house. Starting from the digital competition model of the design, they devise ways of realising it in the desired scale and detailing using 3D printers, laser cutters, scalpels and syringes filled with glue. There can be an almost surgical precision to this work and the results are quite often breath-taking in their own right. If competitions

require a high-end model as part of its deliveries, the model will usually be on display in the canteen before it is shipped off, with architects from all over 3XN and GXN crowding and cooing around it, admiring the details and discussing the materials and technical solutions.



Fig 2.8 3XN Model Workshop.

The model workshop employs 5 full time model builders, architects and designers specialising in the minute skills of the craft, as well as a shifting influx of student model builders from the nearby Royal Academy School of Architecture.

Project Development department

Project development covers the long and varied process that happens once an initial design concept has been greenlighted through a competition win or a nod from a commissioning client. In essence, the teams in the Project Development department are faced with moving a project from design to actual finished building with as few hiccups along the way as possible. This entails hands-on work with competition or design concepts to translate these into construction details in ways that are both true to the original intent and materially and economically feasible. The work throws up a vast array of tasks usually involving refinement or re-creation of the design model to introduce a higher degree of information and rationalisation into projects, gradual elaboration of load bearing

structures, façade detailing and construction details, as well as interior design, materials and products.



Fig 2.9 3XN Project Development.

The Project Development department is also responsible for producing the 3D building information models that structure collaboration during the project's lifetime (projects take everywhere from two to ten years being built depending on planning permissions, clients wishes, partners, and so on), as well and construction documentation – the thousands of 2D plans, sections, and diagrams that are needed on site to build the project. Producing these drawings, the Project Development teams can also be responsible for quality control and error correction in the digital drawings, and economy and risk are naturally key concerns along with buildability and a high fidelity towards the coemption or design concept and renders. Some 40 architects work in the Project Development department stretching through the central ship in the studio.

Business Development department

Business development across Danish, European, Australian and North American markets is crucial for 3XN to maintain invitations to competitions and secure commissioned projects. This includes

monitoring and prequalifying for architecture competitions[11], developing competition teams with external partners when needed, and brief but highly worked over pitches detailing approach, team, and relevant references. The business development team also engaging continuously with existing and potential clients and participate in large scale industry events such as the annual MIPIM property development event in Cannes. Once development activities turn up a project, the team manage project contracts, budgets, and time planning at the early stages in collaboration with project leads from Competition and Project Development departments.



Fig 2.10 3XN Business Development and Communications.

The Business Development team also manage communication activities, publish articles in leading Danish and Global media, feed social media, enter the studio into potential design awards, and prepare leading studio partners for presentations at a large number of lectures, conferences and meetings. In key markets these activities are carried out in collaboration with local PR agencies.

Six full time employees manage business development and communication at 3XN. The Business Development and communications team sit close to the Competition department, close to founder and creative director, and the senior partner and head of design and the senior partner and

[11] Competitions are either open, require prequalification or are by invitation only – the latter two are favoured as this narrows the field of competitors considerably, sometimes from hundreds of participants to just a handful.

CEO. They work in concert with these as well as partners and project leads from competitions, and at times GXN if there are overlapping possibilities for prequalifying the 3XN and GXN team in competitions.

Research department, GXN

And then there is GXN. While GXN is an independent company, its day-to-day work is highly integrated with the practice of 3XN Architects. Demands for innovation amongst leading architecture offices are high and 3XN looks for an edge in a competitive market through sustainable, intelligent, and healthy design solutions. At a more general level, 3XN and GXN are owned by the same holding company, and the business strategy of the studio relies on the two companies.



Fig 2.11 GXN Innovation.

Kasper, the Head of GXN, is a visible figure in international architectural research and increasingly collaborate with the 3XN Business Development department on acquisitions. GXN also works as both a research and development unit maturing risky technologies and ideas to the point where they can be integrated into 3XN project workflow.

As already described the wealth of materials, models, and books expanding across the GXN studio space form visible parts of its particular history – its commitments, projects and connections. New and prospective clients for 3XN usually stop here on their tour through the studio to be dazzled by Kasper, who will tell them that the 'G' in GXN stands for Green, that GXN seeks to change the building culture through an increased focus on people and the environment and that this enables 3XN to do better architecture. As I had settled in as GXN research manager, I would be called on to do these short talks from time to time, and spun the narrative by saying that the 'G stands for Geek'; that we were the geeks to the designers in 3XN, and as such were less encumbered by traditional architecture workflow, which gave us the ability to work on different time frames, forging ahead when exploring new technologies, or pausing for reflection when looking at behaviour in 3XN buildings.

The insights picked up from GXN research work come to influence 3XN design work through 'competition inputs where' GXN teams work alongside 3XN Competition teams to qualify conceptualisation and communication of competition proposals and integrate specific green or human-centred solutions into the design. GXN's *Digital Design* section furthermore work very closely with project leaders and teams in 3XN's Competition and Project Development departments.

Chapter 3: Methods

Ethnographic immersion is well-suited to the study of creativity and social mind in digital design and modelling practices. The study of digital and distributed phenomena has led to productive re-engagement with methods in anthropology (e.g. Hine 2015, Coleman 2012, Burrell 2012, Horst and Miller 2012, Boellstorff et al. 2012). Christine Hine, whose introduction to the ethnography of the internet has been helpful in shaping my own study, puts it like this:

> What seems at first sight obvious—that ethnographers can usefully give accounts of the modes of life that emerge around computer-mediated communications—becomes more problematic when we start to think about where we are going to send our ethnographers, and what they will do when they get there. (Hine 2015:2)

I have covered the *where* in the previous chapter, discussing my construction of a field of study by following the circulation of ideas, people, and projects from the studio of 3XN Architects and GXN Innovation. The present chapter concerns the *what*. What I did when I got there, and how this relates to both theoretical concerns with software, institutions and mind, as well as the specific opportunities that emerged during my work at the studio.

3.1 Questions

'Do you do 3D?' The question for me was simple enough, but eager to make a good impression I immediately began to doubt if I had understood it correctly. Why would I do 3D modelling, I was not an architect. What was I missing? When I said that I did not, the prompt rely was: 'How about 2D?' More grasping. 'No, I'm afraid…' I had a quick think before suggesting: 'I could probably do 1D' I do not remember exactly how this went down, but I remember the excitement of my first meeting with Kasper and Lasse, founder of GXN and head of GXN's consultancy work

respectively, and how badly I wanted to secure a field site for my research at the studio. We were meeting in December 2015 after a brief email exchange to chat about my possibilities for interning at GXN. I had positioned this as a part of my research for my DPhil at the University of Oxford, but had also made it clear that anthropology meant participant observation, and that participation in and around day-to-day digital design work was what I was after. This went down well. Kasper and Lasse were open and energetic in trying to find something for me to do at the studio. But I did not do 3D, nor 2D, and 1D did not seem promising either.

When I began my DPhil, I was motivated by the study of digital design and modelling practice. If I was able to secure an internship with GXN, I could tie this focus to a specific studio, a group of people, actual digital projects. I was interested in a series of questions around the mediated nature of creativity and collaboration in contemporary architecture. Specifically studio spaces, their organisation and technologies, and how these came to shape creative practice. I had been reading work from architects, researchers, and historians on how mathematical description and formal logics were coming to play a key structuring role in contemporary design practice (e.g. Kolarevic 2003, Terzidis 2006, Picon 2010, Burry 2011b, Davis 2013b). Studies of design studios had allowed me to read about how ecologies of materials, objects and even buildings shape everyday work and engineering (Rietveld and Brouwers 2016, Farías and Wilkie 2015, Houdart and Minato 2009, Yaneva 2009a, 2009b, Vinck et al. 2003, Gunn 2002). Recently, anthropology and archaeology have highlighted cognitive aspects of these ecologies, whether through the way they shape socio-material ontologies (Gosden 2008, Douglas and Isherwood 1996[1979]), the cognitive life of things and distribution of minds (Malafouris & Renfrew 2010, Hutchins 1995a) or creative entanglements of thought and materials (Malafouris 2013, Ingold 2013, Rietveld and Kiverstein 2014). The informational and technical aspects of digital tools had yet to be integrated into these

cognitive frameworks in a meaningful way. This was fair game for anthropology and seemed like a task well suited to ethnographic immersion in the studio – in their introduction to a volume on *Digital Anthropology*, Heather Horst and Danny Miller argue that:

> The intention [of digital anthropology] is not simply to study and reflect on new developments but to use these to further our understanding of what we are and have always been. The digital should and can be a highly effective means for reflecting on what it means to be human, the ultimate task of anthropology as a discipline. (Horst and Miller 2012:3)

In this sense, I wanted to take up anthropology's key concern with what it means to be a human, specifically with what it means to be a human maker of things (e.g. Gell 1998, Ingold 2013), through the study of creativity and social mind in digital design at 3XN and GXN. I figured access to the studio space would allow me to investigate how design software and the institutions of the studio came to shape creative thought.

3.2 Access

When I got in touch with GXN in December 2015, I had only just heard about the company a few weeks before. I had been talking to architect friends to get their perspective on who was doing interesting work in the field of digital design and modelling. One had quit the business after working just one year and could only tell me where not to go. Another was still studying and was struggling with access to firms himself. In November 2015, I got in touch with the partner in a design agency I was working at before beginning my DPhil. He was interested in data-driven architecture and had told me to give him a call if I needed advice. He kindly agreed to meet me over coffee one morning when I was back in Copenhagen; he told me at length about his own work in digital design and art and promptly pointed me to GXN. Another good friend and partner in the design agency generously wrote an email introducing me to Kasper (they had met at the 2014

Venice Architecture Biennale). Kasper answered this within a few minutes, and the next time I was in Copenhagen, in December 2015, we had our first meeting as described above.

An anthropologist agonises over access

According to Farías and Wilkie (2015) access to the sites of creative production remains a key problem for the detailed study of contemporary studio practices. Agonies over access is nothing new in anthropology and has always been part and parcel of the discipline. In the 1920s Gregory Bateson was thoroughly vexed by the uncooperative Baining in New Guinea, who tricked him away from their village during ceremonies (Harries-Jones 2016:22). In the 1930s Evans-Pritchard only fared marginally better with the Nuer of Sudan, whom he found distrustful and hostile to him as representative of British Empire (Evans-Pritchard in Burton 1983:283). He did manage to wrangle his famous ethnography from these encounters though (Evans-Pritchard 1978[1940]), which was more than Bateson got from his 'drab' time with the Baining (Bateson 1932:341).

The agonies over access remained as anthropologists turned their gaze inwards and upwards in western knowledge economies (Nader 1972:302, Gellner and Hirsch 2001:5). I experienced my own version of this during my 2015 master's in digital anthropology, when trying to study London's financial quants and high-frequency traders without ever getting in the door of a fund, bank, or trading firm. Instead I made do with a few interviews from sympathetic researchers and documentation of market histories and infrastructure while consoling myself with the experiences of Bateson and Evans-Pritchard. While it is possible to cobble together a study of financial technology through documents on market regulation, infrastructure white papers, and second-hand sources, access to actual sites of practice remains crucial to anthropology. Not least for the study of creative studio based practices, argues Farías and Wilkie (2015:11), because of the comprehensive social interaction characterising creative team work there. Studying situated practices of digital

design and modelling requires access to the sites where this happens. It is worth reflecting on the specifics of this challenge with regards to the studio of 3XN and GXN, as these reflections will tell us something about its practices and institutions.

The fact that I was questioned right away about my digital (3D and 2D) design skills at our first meeting, hints at something fundamental about design practice at 3XN and GXN. As I discovered soon after beginning my internship there, architects at the studio do not draw. They sketch incessantly: personal ideas in their notebooks; compulsive doodles on project documents and meeting materials; throwaway ideas on the rolls of tracing paper that are ubiquitous throughout the office. But compared to the elaborate practices of architectural drawing studied 25 years earlier by anthropologist Edward Robbins in *Why Architects Draw* (1994), the architects at 3XN and GXN do not seem to draw. We talked about this over lunch three weeks into my fieldwork. Lasse, a compulsive doodler who rarely sits without tracing paper and pen in front of him when not on the computer, told us about his first weeks of architecture studies. These were spent with pen and white-out painstakingly drawing detailed sections under the critical eyes of ageing teachers: 'I have never used this since… they turned out super ugly anyway. It would be great though, like the older architects here, to be able to do these tight drawings.' Casper, one of GXN's project leaders shot back: 'But we show up the day after a task is given to us with crazy good visuals instead.' Kristian an intern nearing the end of his six months with GXN chimed in: 'This is one of the biggest myths they tell architecture students: that they should be able to draw!'

Digital modelling and software are ubiquitous at the studio and proficiency in these is a basic requirement for taking part in most of the work going on at there. Which points to another problem for gaining access to sites of creative production. They rely on highly skilled work that requires years of experience with specialised tools to participate in. 'Do you do 3D?' was the first question

asked of me, simply because it would resolve a lot of problems with how to integrate me into work at 3XN and GXN if I did. Like most creative businesses with international scale and scope, 3XN Architects needs to function as a streamlined machine, running projects to tight margins to cover overheads and turn a profit. Efficient and professional organisation of work allows the company to compete successfully in international competitions with slight fees, and manage long term project management and problem solving during design development. There is little room for amateurs here. That I did gain access, while being quite demonstratively an amateur in the field of architecture, tells us something else about the combined studio of 3XN and GXN. GXN is organised differently from the streamlined professional architecture firm. The innovation unit allows the studio to take on riskier, less predictable challenges that do not match with architecture's project workflow. This is central to GXNs organisation and ethos as explained in Chapter 2. And this willingness to take on risky and unpredictable tasks extended to me. While we did not conclude our first meeting with a clearly defined set of tasks for me to do at the studio, we did share an interest in finding some.

While Kasper and Lasse were sympathetic to my research focus on digital design and research practices, Kasper also made it clear on this first meeting that my access to the studio was predicated on my ability to take part in day-to-day work there. In line with this, my level of access was continuously renegotiated as my work at GXN progressed. I got started during August 2016 working closely with Kasper to develop applications for research projects. At the earliest stage my work focused on research into the Danish funding environment, mapping and prioritising foundations and grants which might be willing to support research projects in design and technology. I wrote concept notes for early project ideas, circulated these to potential Danish and international partners, participated in meetings and skype calls. I wrote meeting minutes, and soon

became responsible for translating meeting discussions into draft project proposals, work packages and budgets. As concept notes, meeting minutes, spreadsheets, and draft applications accumulated, so did my autonomy and access to people at the studio.

Conceptualising project ideas often involved experts from across GXN and 3XN. This gave me access to more people through meetings and informal follow-up interviews, and to a growing understanding of how work was organised in the studio.

Exploring possibilities for early stage funding to commercialise GXN's experience with robotic fabrication had me working closely with Morten, one of GXN's key digital designers. While the project was shelved after several months of development work as no funding agreement could be reached, this gave me new access to practical knowledge about applications of modelling in design and fabrication. Another, more successful, development project focused on establishing a shared research cluster within GXN and 3XN to focus on relationships between architecture and behaviour. This included several funding applications – for starting up the cluster; for funding two industrial PhD positions; for cluster projects on design tools and data capture – and had me meeting and interviewing several 3XN partners from the Competitions and Project Development departments, providing new insight in the concerns shaping teams in the studio.

Projects developed during my time with GXN varied in scale and scope, lasting everywhere from six months to four years, but all of them were collaborative in their development and most involved external partners from industry and research. I increasingly met with Danish and international partners from funding bodies, industry, and research institutions, which allowed for a better understanding of innovation and technology frameworks in the architecture, engineering and construction industry. It also helped frame my understanding of design research at GXN and situate this localised practice within a larger globalised knowledge economy (see Chapter 2). Alongside project development I began working as a project manager for several research projects across

GXN's Behaviour Design, Circular Design, and Digital Design sections. In the Digital Design section these included the Digital Factory project, which had me collaborating with Morten and Kenn, the core digital team, as an interim project manager from September 2016 to June 2017. The project sought to develop digital design modelling and robotic fabrication applications. It helped me build a deeper understanding of parameterisation of geometry and modelling environments, which will be described in depth in Chapter 4. I also began working closely with Morten and Kenn on internal development of the Digital Design section through conference presentations, communications work, and discussions of digital workflow in 3XN and how this might interface better with development work in GXN. I will discuss this in more detail below. For now, the point is that project development work gave me access to both localised and distributed contexts for digital design and research in 3XN and GXN, while project management and internal development work showed these practices as they unfolded day-to-day at the studio. Both types of work gave me freedom to circulate through the studio and interview partners and architects, as well as access to a global network of companies and researchers engaged in the same fields as GXN. This work has given an indispensable insight into the political economy of architectural work at the studio, and would not have been possible without this type of professional access to architects, case studies, digital materials, archives, shared drives, and external partners.

Workplace research ethics

As I graduated from an internship position to a project lead for the research stream in GXN I applied for leave of absence from my DPhil from January 2017 to October 2017 since my funding agreements did not allow me to work professionally while pursuing studies. Entering the studio of 3XN and GXN as a workplace gave me the opportunity to further pursue research through participant observation, as well as the space to do additional interviews and case studies. This

allowed me to consider the relationships between digital tools, institutions, and creative practice and mind at the studio in more detail.

To deal with the ethical aspects of working while studying, I devised my research according to the Ethics Guidelines of the European Association of Social Anthropologists and the University of Oxford Central University Research Ethics Committee. As I knew I would be working for a private company on commercial projects, issues of non-disclosure were initially of particular concern. I contacted a research contract specialist at the University of Oxford Research Services who developed a consent clause in my contract with GXN. Signing this provided an opportunity to discuss non-disclosure with Kasper and Lasse; the existence of a formalised contract seemed to give some pause, as GXN do work based on mutual trust and open sharing of knowledge, but the trust established during my early work meant that the contract was signed with no incident.

On the first day of my internship I had asked for time at the GXN start-up meeting to present myself and my work to the full GXN team, including my role and ethical responsibilities. I used this opportunity to discuss issues of consent and anonymisation, namely that everyone would be anonymised by default in my field notes and that no one would be included in my research before explicitly consenting to do so. I also decided not to interview interns directly in my studies to avoid issues with unequal power relations. All recorded interviews were prefaced by written consent forms and opened with a discussion of consent and anonymisation before undertaking recordings, to give people a chance to air and discuss potential causes of concern. I found this to be of very little concern with the people I spoke to. Initially writing the thesis with all participants anonymised, I have since circulated quotes and conclusions to the architects who so generously helped with their time and perspectives, asking whether they would prefer to remain anonymous or go on the record. All participants agreed to the latter, and I include their first names in the thesis as many of the ideas and perspectives shared here have emerged in conversation with them, which they deserve full

recognition for. Reciprocity between researchers and informants is a key problem of ethnography and I am keen to provide something useful for the people who have taken part in my research. As my professional work in GXN evolved, this did indeed seem to be the case and I have been grateful and happy with the fact that people such as Morten and Kenn started including me in their development of GXN's Digital Design section.

3.3 Immersion and analysis

Working professionally at the studio, led to new concerns with negotiating my roles as both researcher and employee, and a focus on how to balance immersion and analytical distance while there. While my fellow anthropology DPhil students were travelling abroad to hang out with tech workers in Silicon Valley (Sutton 2017), filmmakers in Cairo (Khachab 2016), or the contrades of the Palio horse race in Sienna, I was traveling back to Copenhagen. Back the city where I had lived since I was 12, to begin work in an office, which for all its differences resembled work I had been doing for design agencies for six years leading up to my DPhil. Anthropology's key analytical movement is comparative and predicated on this awkward balancing of immersion and distance (e.g. Descola 2005). What, then, does it mean to go back home to study something familiar?

Anthropologist Kirin Narayan (1993) argues for rejecting any distinctions between native and non-native anthropology. This is baggage, she explains, from anthropology's early fixation with the exotic and has always been a gross simplification which hid more than it revealed. Ethnographic research will always be characterised by an uncomfortable chafing of identities and interpretations stemming from day-to-day navigation of shifting relations in the field. This is above all a personal endeavour and as persons we are multiple and impossible to fence into simple categories, such as native or non-native, insider or outsider. Once in the field we straddle these and other dichotomies

and learn through this ongoing navigation. A similar argument has recently been put forward by anthropologist João de Pina-Cabral:

> As a methodology of research, ethnography depends more directly than other less qualitative methods on the personal encounter of the ethnographer with the persons she studies. Its dependence on the achievement of mutual understanding based on the intersubjectivity that results from sharing a lived environment gives ethnography a particular empirical richness and qualifies it ideally for its main aim: the de-ethnocentrification of our scientific understanding of social life. (Pina-Cabral 2017:185)

Narayan and Pina-Cabral highlight the impossibility of clean insider/outsider dichotomies. Ethnography produces knowledge exactly by blurring these boundaries allowing the ethnographer to build mutual understanding through the construction of interpersonal relations. I have already explained above how entering the studio of 3XN and GXN in a professional role widely expanded my possibilities for forging these relations. This produced a style of knowing, which was predicated on productive work encounters shaped by social and practical skills picked up along the way. My own anthropological analytical movement was not so much borne from the distance between immersion at a field site and analytical detachment once away, as it was from the movement through shifting situations within the field in the course of my work (see Ch. 2). These engagements with the contingencies of fieldwork itself, fits well with the outlook of dynamic cultural theory, which posits organisations and people as multiple and inherently relational (Rayner 1992)

Inspired by the work of Steve Rayner (1986, 1992), I see these contingencies as borne from day-to-day navigation of the multiplicity of relationships comprising the organisation of a field of study. Whether I was considered researcher, colleague, friend, or simply someone to be ignored – each work situation entailed learning about a specific set of rules and objectives, as well as the wider institutional context that made them meaningful. And in the end, following Bateson (1987[1972]:166) this type of knowledge production entails an education of attention, learning to

learn with the people one is deeply engaged with in shifting institutional arrangements (see also Rayner 2004:355, Lave and Wenger 1991).

While working at GXN, I began to experience these different institutional arrangements as I became engaged in project development, research projects, consultancy tasks and competition inputs from GXN to 3XN. In these different tasks, I shifted across a wealth of settings from formal funding meetings, freewheeling lunch-time discussions, focused research workshops, tense breakaway sessions, or impromptu competition meetings. I worked alone in front of my computer, with others across meeting rooms and studio spaces, stayed late to meet deadlines and travelled abroad to meet partners and share ideas. This allowed for a participants perspective on the organisational differences between different tasks and organisational setups at the studio (see Ch. 7-9).

To some extent, these type of work situations were familiar to me from prior design and consultancy work but seeing them anew in a different setting, and through my analytical concern with digital materiality, institutions and mind, provided opportunity for comparison and reflection. Following ideas, people, and digital models across situations in and beyond the studio allowed for comparison and clarification of findings as my thinking progressed. To find space for analysis and alleviate anxieties about whether I was gaining traction with my research, I would come into the office early most days to allow for a couple of undisturbed hours to write and formalise my ideas into more detailed notes and articles (Poulsgaard 2019, Poulsgaard and Clausen 2018, Clausen et al. 2020); but in essence my analytical movement was borne from a deep immersion in my work justified from pragmatic approach to multi-sited fieldwork (Marcus 1995, see Ch. 2). As Narayan (1993) suggests, fieldwork has the effect of reframing what we already know from pre-existing experiences; it took me several months of working full-time alongside everybody else to begin to

see the structures and institutions organising day-today work at the studio. As a more fine grained understanding came of the institutional spaces at the studio, the interdependencies between this and digital design practices and workflows began to come into focus.

3.4 Ethnography

Drawing on recent discussions in the ethnography of digital technology (Hine 2015, Burrell 2012, 2009, Marcus 1995), I consider ethnography as both a research practice and way of writing which seeks to uncover interlocking practices, norms, and values around a specific phenomenon; in this case digital design and research at 3XN and GXN. As Christine Hine (2015:29) suggest this is a highly pragmatic endeavour. While theoretical concerns and best guesses can provide for some mental preparation prior to fieldwork, it is impossible to know exactly how specific learning relationships will unfold (or fail to) in the field. Ethnographic methods are varied and adaptable by nature, here I will outline how I came to use these during my time at the studio of 3XN Architects and GXN Innovation.

Participant observation

The pragmatics of digital and multi-sited fieldwork requires adapting participant observation to study digital phenomena that are simultaneously situated and distributed (see Ch. 2). To do this, writes Marcus (1995), we must follow people, objects, and ideas as they circulate through different settings. We must pay attention to digital media's embeddedness in institutions and everyday mundane practices explains Hine (2015). Balance immersion and analytical distance through shifting relationships of identity and power advises Narayan (1993). Eschew distinctions between

what is creative and what is mundane suggests ethnographers of architecture and studio practices (see Farías and Wilkie 2015, Yaneva 2009b, Vinck 2003).

Beginning my internship with GXN, I was seeking to merge these methodological concerns with my own interests in digital design and social mind while also navigating the specific relationships emerging in the studio. I spent my first months at GXN working on project development while observing the studio around me, doing informal interviews, chatting to colleagues, and writing field notes on my computer. I opted for digital field notes when possible but also filled notebooks with a mix of work notes, informal interview answers, and ongoing reflections. I assigned pseudonyms to everybody I spoke to and did not keep field notes on my work computer.

During my initial period at GXN, I was fretting about how to make relationships between technics, practice, and institutions visible. My theoretical concern with studying digital technologies while trying to understand their relationship to social mind seemed daunting. Early studies in human-computer interaction by Lucy Suchman (1987) and Terry Winograd and Fernando Flores (Winograd and Flores 1986) used breakdowns in technology as a methodological ploy for reflecting on what people had at hand and how they related to it. I found this less helpful at 3XN and GXN where design software have become fully integrated into everyday practice. Dealing with the (seemingly) mundane, the field of ethnomethodology and conversational analysis have a productive history of video studies looking at minute interactions and how they structure the flow information and exchange in front of screens (e.g. Lymer et al. 2009, Ivarsson 2010). Suchman's team at Xerox PARC and Hutchins' team at UC San Diego have studied the interactions of people and computers using video recording to great effect (e.g. Suchman & Trigg 1995, Alac 2011, Hutchins et al. 2013). These studies show how minute interactions structure the flow information and the nature of collective decision-making in front of screens. But video was not an option for capturing the

distributed work at 3XN and GXN, as these hyper-situated perspectives tell us little about how interactions relates to larger insitutional realities surrounding these situations, or how structures and learning form one situation spill over into and come to inform the next.

In her introduction to ethnography of the internet, Christine Hine (2015) suggests approaching digital practices as *embedded*, *embodied*, and *everyday*. The efficacy of these perspectives began to emerge as I settled into to both project development and project management work. Immersion in work practices allowed me to see to see how digital design software and models were embedded in various studio contexts, frameworks and institutions (Ch. 9). Project management on digital research projects began to show how the use of digital tools became embodied and highly personal for the architects (Ch. 4 and 6), while ongoing chats and interviews showed how tools became everyday and often treated as unremarkable infrastructure to get the job done (Ch. 8). As my work at GXN evolved, I began to understand the larger context of digital design practices, specifically the organisation of projects and teams in the studio (Ch. 7-9). This meant that my initial concern with digital design tools and practices evolved through concerns about their integration in workflows across GXN and 3XN. In turn, this helped set stage and inspire questions for more formal interviews to explore assumptions with architects at the studio. As observations developed, I was furthermore able to elaborate on what I had seen through more in depth studies of specific digital software and models.

Software and workflow

Doing participant observation at 3XN and GXN helped establish a better understanding of the studio and institutions that digital modelling practices were embedded within. However, to understand relational dynamics between tools, institutions and people, I needed to understand the

configuration of the tools themselves. When I began work as a project manager for the Digital Factory research project in September 2016 this became a professional need as well.

The Digital Factory project will be discussed in more detail in Chapter 4, but in short, the project, which is owned by Danish company Odico Construction Robotics, sought to automate production of formwork for casting curved concrete surfaces by using robots controlling a bendable metal blade to cut through expanded polystyrene blocks. The curvature of the blade is numerically controlled via the mathematical construct of elastic curves. Elastic curves differ from the different ways of describing curvature in most design software today and these again vary from software to software. Approximating curved geometry across these mathematical constructs was the job of mathematicians and robotic experts on the project team. The GXN team was using these approximation scripts to create a parametric design environment that would enable architects to design with an understanding of the limitations and possibilities of robotic fabrication in mind.

Being the interim GXN project manager for 10 months, I helped document some of this work, organise and participate in workshops, and consider applications for additional funding. This required a rudimentary understanding of the mathematical constructs used to describe geometry in the project's design-to-fabrication workflow. Building up this understanding of design software allowed me to spend time with the GXN team as well as robotic experts and mathematicians going through work packages, discussing goals and obstacles, looking over scripts and design interfaces, documenting workshops, and seeing the robots in action. In preparation I was diving into the project files to go through older workshop materials, presentations, and email threads. As I will discuss in Section II, this work helped develop my understanding of what I call *digital materiality*, analysing how the mathematical basis and configuration of different design software come to influence digital modelling work and creative collaboration. It also showed how design research in GXN unfolds with leading partners in the field of robotics and mathematics. And how this work integrates

inspiration and concerns from the wider field of global architecture into research projects, in this case via conference presentations, workshops, summer schools, and studies of high-profile use cases and analysis of specific 3XN projects to understand industry needs for robotic fabrication.

Hine (2015:29) suggests that: 'the "digital" are not available to us in any transcendent sense, but are emergent in practice as they are realized through particular combinations of devices, people, and circumstances.' Working on Digital Factory and doing other development work in the GXN Digital Design section helped show how these combinations of devices, people, and institutions were configured at 3XN and GXN. The robotic fabrication workflow further helped make visible the 'infinite regress of relationships' highlighted by Susan Leigh Star (1999:379, see also Bateson 1986[1972]:251) in her discussion of infrastructure, and how these relationships came to influence each other. This was crucial for pursuing the study of how mind, technics and institutions come to entwine at the studio. What I found during this project were relationships between different expert skillset in the project team, different geometric and mathematical constructs, technics, robots and design software, their integration in situated workshop settings, influence from paradigmatic use cases from the history of architecture, and the stabilisation of these disparate elements in workflows and scripts for modelling design and fabrication. Architect Mark Burry (2011) has highlighted how digital tools allow architects to move from being tool users to tool makers. Tagging along with the GXN Digital Design team helped bring these aspects of the configuration of digital design software into clearer view.

Suchman (2006) highlights paying attention to the situated interaction between people and technics, and how this is configured at the interface of digital tools. Similarly Steve Woolgar (1991), in his observation of software development, discusses how the user is configured by the designer of software. Reading the two side by side with my own ethnography, however, the notion of 'configuring the user' arguably puts too much stress on 'plans' and the legibility of advanced

technical tools to the detriment of 'situated actions' and adaptation (see also Rietveld and Brouwers 2016). Based on my immersion at 3XN and GXN, I would argue that that the shifts between plans configuring the architect as tool user and situated action allowing the architect to become a tool maker works along a continuum with widely differing blends for different tasks, projects, and people. These relationships are predicated to some extent on the digital materiality of the tools and software used, which therefore come to impact creativity and social mind.

Conference case studies

To understand the different relationships between software, institutions and mind, it was necessary to understand how digital models were developed throughout a project and came to be applied differently in the different settings of the Research, Competition, and Project Development departments at 3XN and GXN. A case study of the digital model for the Headquarters of the International Olympic Committee (IOC), designed and built by 3XN Architects in Lausanne, brought the digital connections underlying this organisation to light.

The Design Modelling Symposium is a biannual conference and workshop for practitioners and researchers in digital design and modelling. In September 2017 it was to be held in Paris at the ENSA-V, Ecole Nationale Supérieure d'Architecture de Versailles. Several months before, Kenn had told me he wanted to unpack modelling work on the IOC Headquarters for the conference. He was particularly interested in exploring the integrated workflow developed for the project and asked if I wanted to take part and contribute as an anthropologist. I gladly agreed. In the winter of 2017, we developed our abstract and article for the conference proceedings (Poulsgaard and Clausen 2017). Kenn would talk about the modelling work and his ideas for how to position the article, and I would write and chime in with my understanding of distributed work inspired by Hutchins' (2010) framework of distributed cognition. To build a better perspective of how the IOC project had

develop at the studio, I interviewed the 3XN Head of Competitions and several project leads responsible for its development. I also continued to discuss the project with Kenn and have six recorded interviews and a wealth of notes from these sessions. These conversations enabled a new form of reciprocity. Kenn had the lowdown on the project and a deep understanding of the model as it developed, but I would help structure these thoughts and provide analytical perspective. In the end a mutual understanding of the importance of digital workflows at the studio began to emerge.

When our abstract was accepted, we began developing diagrammatic visualisations of project workflow with input from Morten who was adapting a similar setup for other large-scale projects at the studio, including the CUBE Berlin project, which will feature in Chapter 5. A division of labour quickly emerged, I would formalise interview perspectives and our thoughts in writing, while Kenn and Morten would reflect and provide feedback on my notes. Kenn would develop our way of thinking through comprehensive visualisations of the model and modelling workflow. Often visualisations and notes would chafe uneasily against each other, providing opportunity for further chats and refinement of thought. Our final contribution highlighted how GXN had hacked and adapted design software to configure a digital workflow for the IOC project. This workflow was flexible enough to respond to the different demands emerging though the project as it moved from competition through project development, while stable enough to ensure that project leaders could service project partners efficiently with required data packages as the building was being constructed.

Star (1999) suggests that we should attend to materialities of interaction with technical infrastructure to understand how they support emergent social orders. This simultaneous stabilisation of software and institutions is what the digital design workflow, that we were describing, sought to establish. In line with Star's (1999:379) statement that what we seldom see a single technology, but an infinite regress of technical relationships, I was learning that the IOC

model was not a single file but an ecology of software environments, data-trees, and files cobbled together by Morten and Kenn through adapted and homemade scripts. That this tangle worked efficiently within the studio is a social as well as a technical feat. I will explore this argument in more detail in Section III.

Following on the Design Modelling Symposium, Kenn, Morten and I developed a number of collaborative presentations and articles for peer reviewed conferences, namely Shape to Fabrication in London, April 2018 ("A Platform Approach to the Design and Delivery of Complex Buildings."), Advanced Building Skins in Bern, October 2018 ("Loop, Feedback, Iterate: Collaboration and Modelling in Advanced Façade Design." Published in Clausen et al. 2018), and Innochain: Expanding Information Modelling in Copenhagen, November 2018 ("Practice over Theory: a Studio-Based Approach to Expanding Information Modelling.", published in Clausen et al. 2020). I co-chaired a break-out session on "New Workflows" at the Innochain conference. In developing these conference papers, the ubiquity of digital models and workflows as a hidden organising principle in studio work began to emerge. I began to appreciate, what I had already been reading but not fully grasped, namely that contemporary digital design software and models are fundamentally open-ended, inviting skilled practitioners to hack and redevelop them as they need for specific projects.

In her ethnography of free and open source software developers Gabriella Coleman (2010) has highlighted the importance of personal networks and conference meetings for the distributed communities of practice springing up around software development. Our conference activities showed that there is indeed a vital community of architects, researchers, software experts, and computer scientists engaged with this in European and North American architecture. We would meet the same people at the different conferences, and Kenn and Morten would point out notables

in the digital architecture community to me. As they mingled, I got to test my ideas and assumptions on architects from different firms. I began to see how a host of large-scale firms were developing similar workflows to 3XN and GXN, and as a spin off from these conference activities, we began to have meetings with digital design groups in large-scale European firms, who were interested in the organisation of GXN as an independent research unit.

Interviews

At a later stage in my fieldwork, more formal interviewing provided a venue for elaborating on my understanding of design and modelling practice developed through participant observation and case studies. From October 2017 onwards, I conducted 18 semi-structured interviews with partners, project managers, and digital designer across 3XN and GXN. These interviews allowed me to examine assumptions in dialogue with a wider group of people than the ones I had been working with so far, thereby seeking to refine my findings and understand their applicability to wider studio practice. With 120 employees it was not feasible to interview everybody at the studio and instead I drew up a list of core partners in the Competition and Design Development teams and relied on informal conversations with people across the firm to identify a number of 'digitally minded' architects to talk to[12].

I opted to carry out interviews in the meeting rooms at the office, as I was focusing on people's day-to-day work experience, and also did not want to beleaguer them with too much of a

[12] The gender balance in these interviews skews towards the male end of the spectrum which reflects the network of people I followed, if not the full picture of digitally minded architects at the studio (where overall gender balance is around 40% women). I will not address issues of gender in digital design in this thesis, but will note that several women are prominent in the discipline pushing the bounds of digital design through a diverse body of research and practice, including: Mette Ramsgaard Thomsen, professor and head of the Center for Information Technology and Architecture at Royal Danish Academy of Fine Arts School of Architecture; Billie Faircloth, partner and responsible for research at KieranTimberlake; Martha Tsigkari, partner and working in the Applied Research + Development group at Foster + Partners; Jenny Sabin, Principal at Sabin Studio, Jane Burry, Dean of Design at Swinburne University of Technology; Rivka Oxman, Professor at Technion Israel Institute of Technology; Terri Peters assistant professor at Ryerson University, Neri Oxman, Associate professor at Massachusetts Institute of Technology's Media Lab; Mariana Popescu, postdoctoral researcher at the Block Research Group, ETH Zurich.

disturbance to their work day. Usually I would chat with people over lunch, talk about my project and ask if they would like to do an interview, then follow up with and email invitation with a few notes on the interview to the effect this was supposed to be a relaxed conversation about their own work. Before interviews I provided respondents with a consent form and chatted with them about the research and their role in it to ensure consent before proceeding. I also asked if it was ok to record the interview, which everybody agreed to. In these opening chats I explained that the interviews would be anonymous by default but that I would circulate quotes and findings at a later stage asking people to comment and tell me by then if the wished to continue anonymous or rather 'go on the record'. Everybody generously agreed to do so. I generally found people open and excited to be talking about their interests in digital design and the tools they were using. Hine (2015:50) and Star (1999:381) highlights a potential challenge for talking to people about technology, in that digital tools tend to becomes mundane for everyday users. I did not find this to be much trouble, while people certainly talked about their tool and practice in everyday terms, they were also excited to do so and lucidly discussed different tools and reflected intelligently on their own use of them.

My interview guide focused on understanding 1) the respondent's personal narrative and development as a designer, specifically their interest and engagement with digital design tools and practices; 2) the respondent's placement in the company and day-to-day work practices in order to refine my understanding of the organisation and goals of the differing departments in 3XN and GXN; and 3) the challenges they found in working creatively and collectively with digital tools. These three main concerns helped form a loose structure for the interview, but once respondents had relaxed into the initial questions about themselves and their interests, interviews often unfolded as more open-ended conversations. To guide the thematic content of the conversations but not their tenor, I used Charles Spradley's (1979) methods of asking grand tour questions to allow the

respondent to describe a theme in their own words, then using their wordings to do follow up probing and elicit specific examples from their current work while asking contrast questions to explore distinctions within this. During the interviews I also posed my working theories to respondents allowing them to reflect and criticise; often this would take the form of ongoing reformulation of the ideas I had proposed, which helped me gain a better understanding of how architects at the studio perceived my theoretical concerns and findings. I found that most people I interviewed had a wealth of personal reflections from working with digital tools, whether through close attachments to tools used during learning and training or specific models or scripts developed during project work. Their excitement for specific tools was contagious and often we spent some time chatting about the merits of this tool over that or why project specific scripts were worthy of attention. These chats quickly evolved into a discussion of the wider context of digital modelling at the studio. Everybody I spoke to without fail emphasised that their work was essentially part of a wider collaborative context. This had both positive and negative consequences, they explained. On the positive side were the joys of collaborative development and creativity (though few informants also professed a wish to explore tools on their own, in general more experienced architects emphasised collaboration, when compared to less experienced). More troublesome, was the fact that scripts become highly personal for their designers and therefore quite hard to collaborate around.

Further findings from these interviews will be elaborated in the following sections. Section II will focus on the technics and models of digital design at 3XN and GXN, Section III on how these tools are utilised in collaborative practices at the studio.

Section II – Technics

> If we could rid ourselves of all pride, if, to define our species, we kept strictly to what the historic and the prehistoric periods show us to be the constant characteristic of man and of intelligence, we should say not *Homo sapiens*, but *Homo faber*. In short, *intelligence, considered in what seems to be its original feature, is the faculty of manufacturing artificial objects, especially tools to make tools, and of indefinitely varying the manufacture.* (Bergson 2005[1944]:154 quoted in Malafouris 2013:154, emphasis in original)

In his book *Creative Evolution* (2005[1944]), philosopher Henri Bergson argued that the defining feature of humanity was neither intelligence nor rationality but rather how these traits manifested in an endless variety of tools, specifically 'tools to make tools'. Digital computers are only one instance in a long line of such 'tools to make tools' extending the creative capacities of our species (Malafouris 2013, 2014) but seem qualitatively different in their flexibility, scope and power.

Digital tools are at heart about modulation and abstraction, resting on the recursive nature of code and the formal logics of mathematics and software (Kelty 2008). In architecture, computation has introduced new types of digital 3D and information-based models into design, which in turn have unleashed a wealth of novel practices (e.g. Lynn 1993, Aranda and Lasch 2006, Hight and Perry 2006, Gramazio and Kohler 2008, Burry 2011b, Banke 2013).

Architect Mark Burry (2011) has argued that design software and scripting have empowered a new generation of architect tool users to become tool makers. Digital tools let designers build computational scripts and 3D models, where geometry translates to data, and data to geometry. This shared informational basis permits functional integration across a wide range of software environments allowing for manipulation, combination and re-use of inputs and outputs from models across all phases of architectural design. In this sense, scripts and models are tools created using other tools, namely design software and coding languages. Digital tools allow for easy creation of advanced 3D geometries. They integrate the mathematics that underlie these into digital models that expand from being design tools to also becoming vital parts of creative practice at 3XN and GXN.

Software, materiality and agency

Cognitive archaeologist Lambros Malafouris (2013:154) cites Bergson on 'tools to make tools', to argue that there is more to Homo Faber than the sophistication of our technologies. For Malafouris, what really matters is the intricacy of our engagement with tools, and the way this engagement come to shape our species evolution. Humans are prosthetic beings, argues Malafouris, extending their bodily and cognitive faculties via technical prostheses (see also Stiegler 1998). In this perspective, we cannot escape the transformative influence of technics on ourselves as little as we can escape the evolutionary history of our species. Technics is a constantly evolving prosthesis for the creative extension of our imagination, including our ability to design and fabricate things, objects, and buildings.

This perspective is at the heart of Malafouris' (2013, 2014, 2015) Material Engagement Theory (MET), which argues that the very materiality of our tools and the world around us becomes part of our minds. He uses the analogy of the 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 must feel and follow the clay as the pot emerges through dynamic transactions at the wheel. 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). Creative agency is not resting with the potter, but emerges in the dynamic coupling between potter, wheel, and clay.

I will argue that there is a similar materiality to digital tools. I call this *digital materiality*. Digital materiality is constituted by the way these tools operate and are configured. Basic geometric shapes, formulas for describing and manipulating geometry, the configuration of software, and the screens and interfaces used in modelling, all constitute digital materiality which becomes a medium for creative extension of mind for architects at 3XN and GXN. This section of the thesis is about this medium, how it is composed, how it is configured in software, scripts and digital models at the

studio, and how architects continuously experiment with it to better understand its creative possibilities. This speaks to the wider analysis in the thesis of how dependencies between institutions and technology come to form a rich environment for the creative extension of mind over timescales ranging from minute interactions in front of screens to the long development of architecture and research projects.

Chapters 4-6

The following chapters are structured around core concepts explored through my fieldwork, namely digital materiality, modelling platform, and design research. These concepts will be central to examining how digital materiality shape creative and social mind in modelling practice at 3XN and GXN across the scales of code (Chapter 4), models (Chapter 5) and screens (Chapter 6).

Chapter 4 examines a GXN research project seeking to develop workflows for designing and fabricating advanced geometry in architecture. I use this project to further define the concept of *digital materiality*. This concept describes the way successive layers of mathematics, code, and software come to mediate and shape architects' screen-based creative work. Just as molecular materials (such as clay), come to transform action with material objects (such as pots), so digital materiality come to enable and transform creative practices with computers.

Chapter 5 examines how the digital materiality of different design software are brought together in digital models at the studio of 3XN and GXN. I discuss the model as a distributed platform that integrates a variety of practices and logics. In anthropology, the notion of cognitive ecology argues that mind is essentially a distributed phenomenon. I will argue that the digital *modelling platform* is

a vital element of cognitive ecology at 3XN and GXN, and that the architects' process of mind are extended and materially anchored in practical engagement with platform.

Chapter 6 further elaborates on the computational modelling environment at 3XN and GXN by investigating screen-based *design research*. Work in front of screens is at once virtual and material, combining a seemingly endless array of possibilities with the constraints and affordances of digital materiality and studio workflows. The chapter explores how architects situate themselves within this environment to establish a sense of scale and feel for their tools which allows them to turn the potentials of computational design software into creative possibilities.

Chapter 4: Code

What is the role of software in architectural design? Who designs, the architect or the digital tool? With the growing prevalence of software in studio work, digitally-minded architects at 3XN Architects and GXN Innovation are enquiring into the relationship between their tools and their designs. Here, I draw on the work of cognitive archaeologist Lambros Malafouris (2013, 2014, 2015) to argue that digital design tools have their own materiality, which come to shape the architects' work. I define the concept of *digital materiality* to describe the way successive layers of mathematics, code, and software come to mediate and shape creative mind in digital modelling. Just as molecular materials act as resistance and come to transform action upon material objects, so digital materiality come to enable and transform creative practices upon computers. This has consequences for our notion of agency. Malafouris (2013) has advanced the notion of *material agency* to describe how materials and technics mediate our possibilities for acting in the world. In this view, creative agency is the relational and emergent product of people's material engagement. I examine this concept as it relates to digital materiality and digital modelling practices observed in my fieldwork with the GXN Digital Design section.

4.1 Digital Factory

The Digital Factory project intervenes directly into discussions about the relationship between digital and physical materiality in architectural design. The project enables a definition of the concept of digital materiality and shows how architects at GXN engage with technical research projects to expand their understanding of digital design tools and build the know-how required to create and manage digital models at 3XN and GXN.

Bladerunner and Digital Factory

My notes from the workshop records our shared excitement in the moment. Our little group of architects, mathematicians and robotics experts are clustering together in the large warehouse watching the machines in front of us. No one is saying a word but noises from a host of robots, lifts, and drills fill the warehouse with hum and echo. Behind us robots slide along tracks, move and rotate their arms as they cut and mill through large white blocks of expanded polystyrene (EPS). Other EPS blocks are stacked in tall clusters along the walls and in between the robots. Worked EPS is all around us, large letters cut from foam, twisting geometrical shapes, full-scale bits and pieces from technical experiments and commercial projects.

Minutes earlier we have inspected a beautifully curving concrete bench, designed for the Mathematics Gallery at the London Science Museum by Zaha Hadid Architects. Its design and fabrication have made the smooth concrete seem almost fluid in its drawn out curvilinear form. Close by, a white block is being milled into a full-size horse's leg; the bright orange ABB robotic arm move fluidly around the rotating leg, hoof and muscle already visible, while white EPS chips fly all about and collect in large piles of static electric dust around it. But this is not what we are looking at. We have our gazes fixed at a square white block, some 90 by 90 centimetres, being pushed slowly towards us, offered up by a robot arm while two other arms shift and twist at its sides. The glistening sound of EPS being burned reminds me of the making of microwave popcorn as a faint trace of smoke betrays the progress of the hot metal blade melting its way through the block while controlled by the two twisting robots at its sides. Once the block has been pushed all the way through the blade, a dash of brownish smoke escapes and everybody rushes forward to lift the newly separated halves of the block apart and inspect the cut.

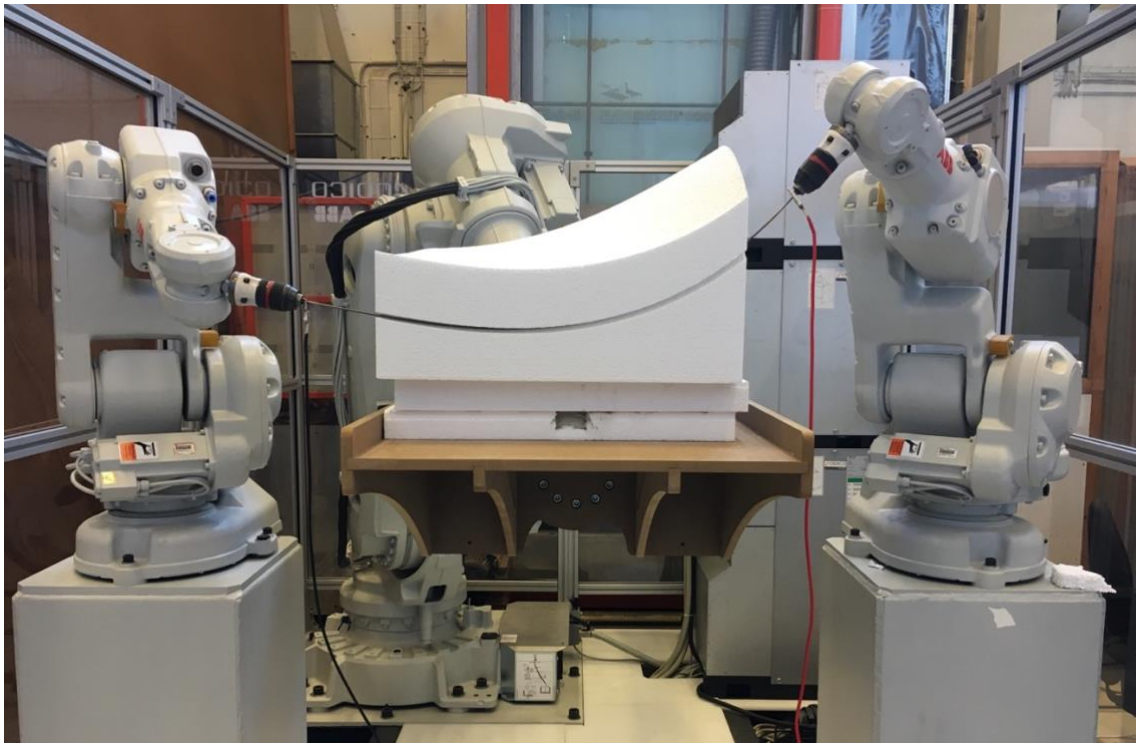

Fig 4.1. Digital Factory Robotic Hot-Blade Cutting workshop setup.

The Digital Factory research project[13] is run by Odico Construction Robotics, a five-year-old Danish start-up whose warehouse in Odense is the scene for our workshop this March day in 2017. The research team has been collaborating since 2013 to develop a toolbox of applications for robotic arms. Along with a preceding project called Bladerunner, Digital Factory pioneers a technique known as hot-blade cutting. This technique numerically controls the curvature of a blade slicing through EPS blocks. The goal is to vastly reduce the cost and accelerate the speed of production of formwork for curved geometry in architecture. In construction, curved concrete is mainly cast using bespoke formwork and moulds for pouring concrete into desired shapes. As in

[13] The work presented in this chapter was developed within the two 3-year research projects, 'BladeRunner (2013-16)' and 'Digital Factory (2015-18)' supported by the Innovation Fund Denmark, as part of a larger effort in development of robotic hotblade cutting manufacturing methods. The BladeRunner project is developed by partners Odico Formwork Robotics Aps (project lead); the Technical University of Denmark, Department of Mathematics and Computer Science and Department of Mechanical Engineering; the Danish Institute of Technology; 3XN Architects and GXN Innovation and Confac A/S. Digital Factory is developed by partners Odico Formwork Robotics Aps (project lead), the Technical University of Denmark, Department of Mathematics and Computer Science and 3XN Architects and GXN innovation.

any industry, bespoke items are laborious and expensive to produce. Digital Factory seeks to reduce the cost of this by connecting robotics, mathematics, and design software to enable automated production of formwork at much higher speed than usual. The project brings together robotics experts from Odico with a team of mathematicians from the DTU Compute Department of Applied Mathematics and Computer Science at the Technical University of Denmark, and architects from the Digital Design section at GXN Innovation. GXN are helping the team understand how to introduce hot-blade cutting in commercial architecture projects by providing potential use-cases from the 3XN project portfolio, and by seeking to incorporate fabrication software into popular 3D design software used in architecture. The goal is to allow non-expert architects to use the Digital Factory setup thereby increasing its reach and value.

Presently, when an architect has created curved geometry via a digital 3D modeler this does not export smoothly to production files for the robots, as the software used by architects and fabrication robots is not fully compatible. Digital Factory takes aim at this incompatibility by developing a workflow – a series of integrated digital steps for design and fabrication – that enable architectural design software to communicate with the control code of industrial robots. In this way, production planning can be integrated directly into digital architectural models from early design phases to evaluate whether designs meet construction constraints of the robots.

Odico estimates a considerable market for production of formwork. So does the market it seems: when Odico went public in June 2018, the company closed out its IPO on the NASDAQ First North exchange with securities oversubscribed by 300%, valuing the company at GBP 14 million. In getting there, the Digital Factory project was funded with GBP 560.000 and Bladerunner was funded with GBP 1,5 million by the government backed Innovation Fund Denmark (IFD), which provides funds for high-risk, high-reward technology projects in Denmark.

Design to fabrication

As these public and private investments show, there is a palpable sense of opportunity surrounding automation in the architecture, engineering and construction industry, which according to consulting firm McKinsey (McKinsey Global Institute 2017) shows the lowest productivity growth of any sector in society. Part of this lag, McKinsey speculates, results from the lack of standardised processes in construction, which still require a high degree of custom production that does not lend itself well to industrial models of automation (compared for example to cars or mobile phones which have high output and low variation in production). New fabrication techniques promise to marry automated construction with high design variability by creating integrated design-to-fabrication workflows (Søndergaard et al. 2016, Brander et al. 2016, Søndergaard and Feringa 2017). When I first got involved with the project, Morten who was the GXN project lead for Digital Factory, excitedly explained how designers that were able to work efficiently with the dependencies between computation, design, and fabrication could realise bolder designs at lower cost.

Enabling bolder design is in large part what Odico's Digital Factory project is all about. A core innovation in the setup was pioneered in the Bladerunner project and lies in the dynamic control of a bendable metal blade using robot control code and a branch of mathematics named 'elastic curves'. This allows for production of doubly curved surfaces, surfaces that curve in two directions at once, which are hard to manufacture manually but increasingly easy to design with the advance of computational modelling software. The use of doubly curved geometry is on the rise in architecture thanks to digital design tools (e.g. Burry 2011a) but is often prohibitively expensive to construct due to the need for bespoke formwork for casting concrete into curving form. Addressing this, Odico's robots enable parametric production of double curved and other pieces of advanced formwork. It works like this: a heated metal blade is suspended between two robotic arms while a third robot pushes an EPS block through the blade. As the curvature of the blade can be

manipulated in real time through numeric control of elastic curves, the shape of the cut can be translated from digital design software to robotic fabrication. Make the cut, pull the separated halves apart and you have a curving piece of formwork which can be used as part of a mould for casting concrete surfaces. Rinse, repeat. Stack the blocks to achieve the desired shape and size, apply coating if finish of the surface is important, and use the form to cast concrete into a freely curving building element. These moulds have already been used experimentally by 3XN and GXN and have been part of realised projects such as Zaha Hadid Architects' Mathematical Gallery at the London Science Museum and Olafur Eliasson's Kirk Kapital headquarters in the rolling landscapes of Vejle Fjord in Denmark.

Workshopping the design to fabrication workflow

At 7.30 in the morning of the first day of the Digital Factory workshop in March 2017, Morten, Kenn, Sean, and I met at the Copenhagen Central Station hurrying on to a train to Odense, where in a few hours the workshop would begin.

Morten was the project lead for the GXN Digital Factory team. Morten and Kenn form the core of GXN's Digital Design section and both had been involved with the robotic fabrication project from its beginning in 2013. Sean and I had been involved with the project for seven months but had yet to see the robots in action. Sean had interned with GXN and had helped develop scripts for generating curves to be used as input for the work of the DTU team of mathematicians developing algorithms for control of the curving hot-blade. He was now hired as an architect at 3XN but had taken the day off to 'go see the robots.' I had become part of the project team as an interim project manager seven months earlier, when I began my internship with GXN. This job consisted for the most part in sorting out planning, emails, coordination, and to a lesser extent project development, and had provided a way of proving myself helpful to the Digital Design section.

To pass the time on the train between Copenhagen and Odense we discussed our expectations to the days ahead. The prospect of seeing the robots in action after months of development work had us all genuinely excited. As Kenn had told me a few days earlier, practical workshops like this turn months of work in front of screens into tangible material results. Morten and Kenn might have seen the robots work before, but as they pointed out in our preparation for the workshop, there remained many issues to test out with the workflow they had been developing. The goal of the workshop was to see how the work of the mathematicians could be integrated into the design workflow developed by GXN, and further how this would integrate with the larger robotics setup developed by Odico. The workshop was testing mathematics, scripts, and software to gauge their effects in the material world of robots, blades, and EPS. This shift from digital to physical materiality caused both excitement and anxiety, as this would show not only the efficacy of the workflow but also, invariably, its problems. Turning code and digital models into material form would provide an opportunity to stress-test the design-to-fabrication workflow, identify issues and work through them with the team all together in one place.

Kenn vividly remembered a prior workshop, working with the Bladerunner team, the robots, and workflow right up to deadline the year before at the Rob|Arch conference in Sydney. The thrill of pulling through just in time to deliver a good workshop for the participants still animated his story as he explained how the team had worked around the clock testing the robots, getting errors, fixing buggy scripts before finally arriving at a setup that worked. His conclusion to the story: ‘we made it, we always make it somehow,’ served as both a satisfying conclusion to an engaging story, and a morale booster in the face of the buggy scripts and technical glitches that we were sure to face in the coming days. It was not the first time Kenn had told this story, in my notes from one of our earlier GXN meetings, I had jotted down the same story, with Kenn explaining:

> What really worked in Sydney was having the workshop to integrate all of these components [scripts, workflow, robots] into workable tools. It was easier for us to work together because we had a clear idea about the use – get something ready for non-experts by the time of Sydney – and a hard deadline.

In digital design research, workshops like these work well by focusing a team with different expertise and expectations around a well-defined common goal, in this case demonstrating a workable design to fabrication workflow and testing this by feeding the robots with geometries and designs to cut. The excitement we all felt towards the workshop touched on the wider architectural and business opportunities described above. But a much more immediate excitement stemmed from the sheer anticipation of coming together as a team to turn months of work into something tangible that would send several tonnes of industrial robots into action (see also Yaneva 2009a:25).

4.2 Computation of form

The possibility for bridging design work and robotic fabrication, which had us so excited, rests on advances in computer graphics and computer numerical control of machines. Digitisation of both geometry and industrial machinery ties design and production into the digital domain. Architects speak of Computer-Aided Design and Computer-Aided Manufacture (CAD/CAM) to describe this convergence. The robotic fabrication processes we saw in the Odico warehouse can demonstrate just how much work is required behind the scenes to bridge digital design and fabrication.

Computer Aided Design and Computer Aided Manufacturing

Computer-Aided Design (CAD) describes the field of computer graphics, software development, and interaction design that enables description and manipulation of 2D and 3D geometry on screens. Computer-Aided Manufacturing (CAM) describes the field of automated production,

which seeks to translate code from CAD into instructions to industrial robots, milling machines, laser cutters, and 3D printers. (Kolarevic 2003) Contemporary architectural research is abuzz with excitement for digital design and fabrication. Digitisation is seen to overcome divisions between architecture and its means of production, which has been in place since Renaissance masters such as Leon Battista Alberti formulated architectural notation systems in a bid to set designers apart from builders (Carpo 2011). As Morten had explained to me early on, these digital tools hold the alluring potential for architects to realise bolder designs at lower cost by giving them renewed control of the fabrication process, and by extension control of important decision-making during construction which can influence the final building.

Architects were not always this bullish on Computer Aided Design. Architect Mark Burry remembers his introduction to CAD in the 1970s at the University of Cambridge under the auspices of CAD pioneer William Mitchell:

> …once a week for a semester we went down to the university's computer centre where we would do the maths and valiantly punch cards to input the computer with the necessary analogue binary data. At the end of the semester I had computer-drafted a cube that could be viewed in perspective; an inauspicious introduction to design computation. … I took absolutely no interest in the field…. (Burry 2011b:14)

Today, Burry is amongst the leading innovators applying digital design and fabrication to architecture. He was executive architect at Antoni Gaudí's Sagrada Família basilica in Barcelona from 1989 to 2016, where he pioneered digital design and fabrication techniques to complete Gaudí's largely unfinished and wholly un-notated designs (Burry 1993, 2005, 2011a, 2015).

William Mitchell (2003), in whose Cambridge laboratory Burry first wrangled with computers, succinctly describes the inner workings of a CAD environment. The basics are a set of given *geometric primitive shapes* that are not derived from other shapes. Historically, Mitchell notes, architects worked with the simple shapes of the straight line segment and circular arc, basic elements in Euclid's geometry, which were embodied in the architectural tools of straightedge and

compass and formed the basis of Renaissance notation systems. Today the primitive shapes also include 3D solids such as cubes, cones, and spheres (fig. 4.2). To these primitive shapes are added rules for basic *geometric transformations*, such as rotation, reflection, and scaling. And to these rules for transformation, Mitchel explains, are added logics for *combination operations* that allow to build more complex shapes from the simple ones already given.

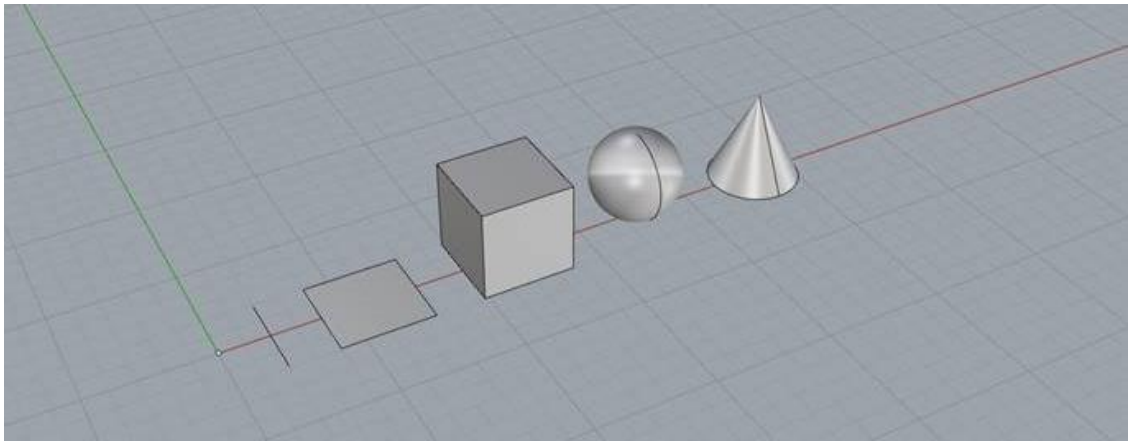

Fig 4.2 Geometric primitives: point, line, plane, cube, sphere, cone.

A CAD system relies on primitive shapes, their geometric transformations, and the ability to combine shapes into new forms. These functions are described in the underlying mathematics of primitive shapes such as lines and curves, and their geometric transformation, along with Boolean logic for combination operations. The simplest *geometric primitive* is a point, representing a zero-dimensional location in 3D space described by x, y, z coordinates. One dimension up we find the line segment, representing an infinite number of points between two end points. And up from this, we find two dimensional planes, and then basic 3D volumes such as cubes, cones, and spheres. Geometric primitives can be represented by the software in different ways. That is, the underlying mathematical formulas used to describe the dimensions and transformation of primitives can differ and some software use different underlying mathematical formulas to describe and manipulate geometry. I will explore this further in Chapter 5, but for now will simply note that the different

mathematical ways of describing and manipulating geometric primitives means that not all design software necessarily speak the same mathematical language. One reason for this diversity lies in the different possibilities for control and manipulation offered by different mathematical constructs and how they dovetail with the overall goals of different software. The different geometric primitives of 3D software means that transferring designs from one software environment to another can be cumbersome and require a lot of digital translation in between.

Using the Digital Factory workshop to explore this work ethnographically, I will elaborate on the concept of Digital Materiality. I will discuss how architects at 3XN and GXN engage with the nuts and bolts of their digital design environments and how, through this work, they come to build up a intimacy with their tools that allow them to work fluidly and creatively with them – in short how digital materiality enables the creative extension of mind for skilled digital architects.

Elastic curves, Bézier curves, and NURBS curves

After Morten, Kenn, Sean and I arrived at Odico's facilities in Odense, we met with the rest of the team over breakfast while the Odico project lead recapped our agenda for the day: test the current iteration of the design-to-fabrication workflow by designing and cutting single and multi-block designs. Before long we were diving into the finer mathematical points of the Digital Factory workflow. A PhD with the DTU Compute team was presenting her work, showing slides with sets of blue and yellow curves lying on top of each other. Some of these blue and yellow curves followed each other very closely, some were clearly off (see reproduction of curves in fig. 4.2).

The yellow curves, she explained were *elastic curves*. Elastic curves are a mathematical construct for describing the shape assumed by an elastic rod – for example a bendable metal blade – when pressure is applied to its endpoints while its tangents are being controlled. Elastic curves are key to the Bladerunner and Digital Factory technology since they enable numerical control of the

heated metal blade slicing into the EPS blocks to cut moulds. By knowing the material of the blade, and controlling its end points with two robots, the shape of the blade can be manipulated in real time while a third robot pushes a block of EPS through the curving blade (see Brander et al. 2016). In this way, the robotic setup can effectively automate the fabrication of almost any curved surface.

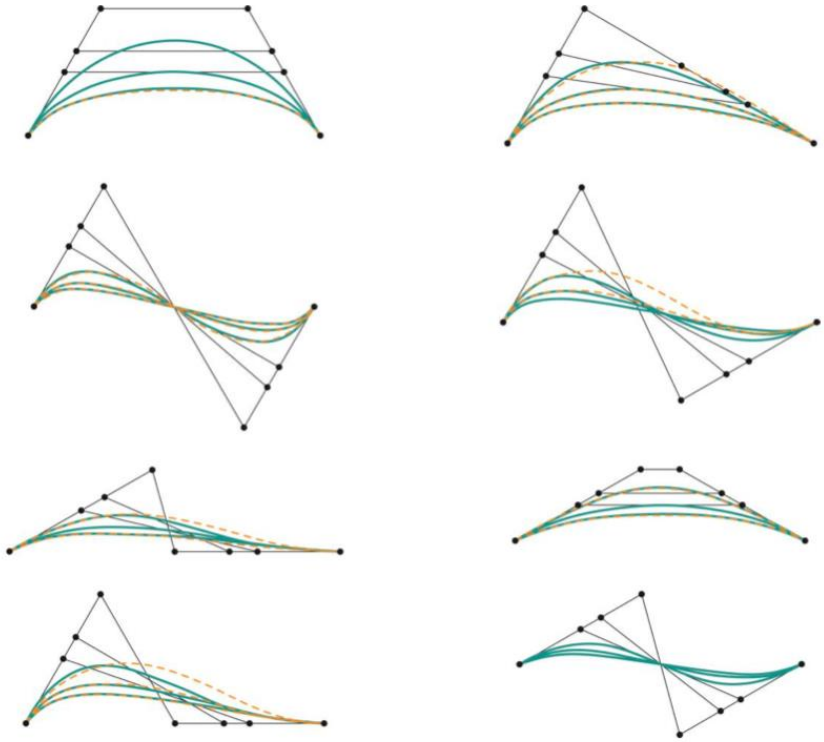

Fig 4.3. Approximation of Bezier curves (blue) to elastic curves (dashed yellow), the black dots are the Bezier curves' control points described below (from Brander et al. 2016:318).

The blue curves, the DTU mathematician explained, were *Bézier curves*. Bezier curves is another mathematical construct for describing and manipulating a curving line segment.

A Bézier curve is defined by a set of *control points* (fig 4.3). The first and last control points are always the end points of the curve but intermediate control points generally do not lie on the curve, and you can imagine the curve taking on its shape as it is stretched out between its control points. Move a control point and you will change the curvature as well. This graphical representation as

curving lines segments with a series of control points connected to it makes the graphical manipulation of Bezier curves comparatively easy and intuitive, far removed from the complexities of the polynomial expressions that make them work mathematically. Their robust underlying mathematics and their intuitive graphical control means that they offer great flexibility and precision for digitally modelled curves and surfaces and they quickly became an industry standard after their development in the 1960s.

Today, much CAD software relies on a subset of Bézier curves called Non-Rational Uniform B-Splines, or NURBS (B-Spline is short for basis spline, a mathematical function describing the smooth curvature of a line segment). *Rhino*, which is one of the most popular 3D modelers used by architects today, relies on NURBS, and NURBS are therefore key to any digital workflow that seeks to reach as many architects as possible.

To understand how this impacts the Digital Factory project it is helpful to think of the three types of curves – Elastic, NURBS and Bézier curves – as three mathematical operating systems for manipulating digital geometry – for example macOS, Windows, and DOS – while keeping in mind that these three operating systems are not necessarily compatible. In this example, elastic curves are the operating systems for the numerical control of the robotic hot-blade system, NURBS are the operating system for manipulating geometry in Rhino. To interpolate between the two, the DTU team of mathematicians explored the use of Bézier curves as these can be very close to elastic curves under certain mathematic conditions (Brander et al. 2018). In essence, what they were working on was finding better ways of making the different mathematical operating systems of CAD and CAM within the Digital Factory project compatible by approximating from input geometry described by NURBS curves in Rhino to elastic curves, which could be used to control the metal blade in the robotic setup. The finer points of this work remain in the domain of mathematical research and computer science. My overview hardly does justice to the 5 years of

work put into approximation and control of geometry by the DTU Compute team (see Brander et al 2018, Brander et al. 2016). But what should be clear from this brief overview is that even though the revolution in CAD/CAM harness the digital power of zeroes and ones, a lot of work is required for achieving computer numerical control of geometry, and several layers of mathematics, code, and software mediate the relationship between what an architect inputs via mouse or keyboard, what she sees on screen, and what a digital fabrication system will output. These mediating relationships are part and parcel of the overall thesis argument that the digital materiality of different design environment come to enable different types of interaction and collaboration.

4.3 Designing with Digital Factory

The mediating relationship of mathematics, code, and software is important for Digital Factory. The idea behind the project is that the robotic setup should be able to cut geometry in minutes using input from Rhino to increase its usability and reach in architecture. This means that designs from Rhino must be mathematically transformed from NURBS input to elastic curves for cutting. And this poses a number of problem as the transformation is non-trivial and some regions of a design might turn out to incompatible with the robotic-hot-blade setup (Brander et al. 2016:313).

Instead the Digital Factory team was seeking to develop an automated workflow for approximating from NURBS to elastic curves – with Bézier curves as intermediary – at high speed and precision. Speed and precision allow for real time feedback to architects thereby enabling them to create fabrication ready geometries directly in Rhino by seeing the approximation happen in front of them on screen as they create an manipulate geometry. This workflow for design and real time approximation was what the team was seeking to test at the workshop.

Digital Factory workflow

The mathematicians use a number of programming environments and languages to create algorithmic scripts for approximation. It was the task of the GXN team to integrate these approximation scripts into the Rhino design software environment utilising its Grasshopper visual scripting interface. Grasshopper is a popular add on to Rhino. It provides a visual interface for stringing together series of operations into visual scripts represented by small boxes and a myriad of connecting lines between them (fig. 4.4). The visual Grasshopper scripting interface provides a relatively simple entry point into coding in architecture, and Rhino and Grasshopper have become key software in the field. The intuitive on-screen manipulation of geometry in Rhino is familiar to most architects today, and the open-ended nature of Grasshopper allow for integration of different tools, which can be easily accessed and manipulated by more adept digital designers.

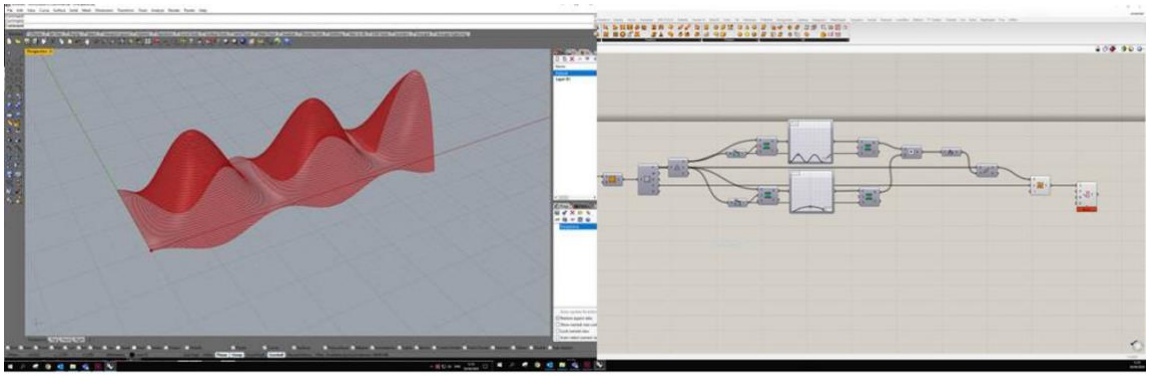

Fig. 4.4. Rhino viewport for manipulation of 3D geometry with Grasshopper scripting canvas.

At the March 2017 workshop, Morten presented GXN's work using the visual canvas of Grasshopper as cue to walk through the current Digital Factory workflow step-by-step. Moving through clusters of Grasshopper functions, Morten explained how GXN had integrated DLL files with the approximation algorithms from the DTU team into the design workflow. DLL files are Dynamic Link Libraries that contain a collection of executable functions, such as approximation algorithms, which can be run as black boxes. The DLL files from the DTU team take input

geometry from Rhino via Grasshopper, runs the approximation in Grasshopper, and returns approximated curves and surfaces to the Rhino viewport.

Morten thanked the DTU team for simplifying the code and happily explained how the new approximation algorithms ran at much faster speed than what we had seen before – several times faster – a point he underscored by running approximations on screen as we were watching.

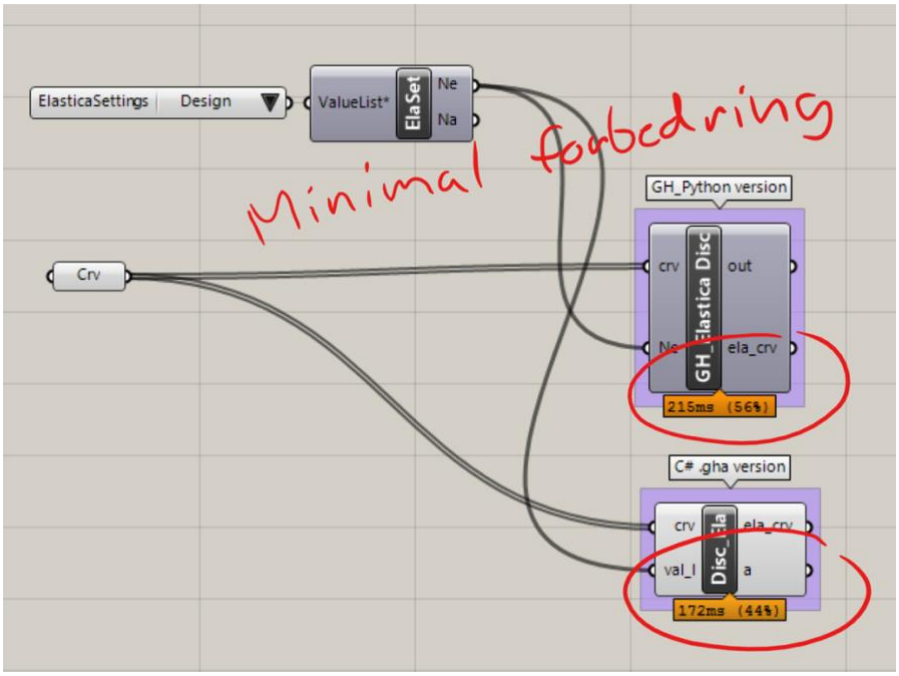

Fig. 4.5 'Minimal improvement' attachment in mail from Morten to Kenn and me following the March 2017 Digital Factory workshop: 'Have integrated Discrete Elastica written in C# in .gha, though only with minor improvements to speed 😉.. time to break out the multi-core.' Collaboration between Morten and the DTU mathematicians sought to improve approximation time by updating the code from Python to the C++ programming language before integrating this in Grasshopper ('.gha'). C# enable multi-core processing, parallel computation, to improve computation speeds.

Close collaboration between Morten, the DTU mathematicians, and the Odico robotics team before and after the workshop sought to improve approximation robustness and time by updating algorithms and changing code from Python to C++ (fig. 4.5). This preoccupation with programming languages betrays the importance of the layers of mathematics, code, and software that mediate relationships between what an architect inputs with mouse or keyboard and what she sees on screen.

As the DTU Compute PhD had explained at the outset of the our workshop, sometimes input and approximation were incredibly close in the project; sometimes they were not, meaning that the approximation had real and varying impact on the final geometry of fabrication-ready designs.

Single block design research

After presentations in the morning, the Digital Factory group sat down to work. I joined Sean from the GXN team as he opened the Rhino and Grasshopper design interface to create single block designs which could test out the workflow and be cut to calibrate the robots later in the day.

The main interface of Rhino consists of four rectangular viewports providing different views of 3D objects in x, y, and z dimensions. Grasshopper, in contrast, presents a flat canvas, where boxes with computational functions can be dragged and connected up with myriad lines in-between describing the step by step execution of a script. As explained earlier, the two are connected so that geometry from Rhino can feed into and be manipulated in Grasshopper. Sean kept the two windows open side by side so that he could work on both geometry and scripts continuously updating between the two and seeing the results (fig. 4.6).

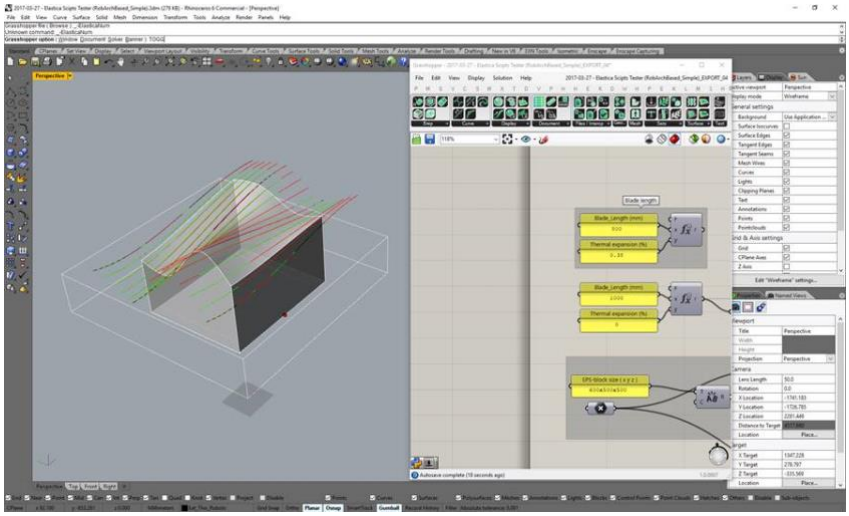

Fig 4.6 Digital Factory Rhino and Grasshopper workflow.

Sean immediately started adjusting several settings in the Rhino viewports quickly clicking checking and unchecking boxes to get the views he wanted. When I asked him why, he distractedly replied: 'I just change it so that it is more like I like it…' Christian Heath and Paul Luff (2000:161) suggest that part of the efficacy of CAD software lies in its ability to be adapted into different virtual environments for different types of work. By configuring the Digital Factory setup and viewports, Sean was tweaking the design environment to better fit his needs – configuring the software to configure his own use of it, to paraphrase Steve Woolgar (1991).

After this adjustment, Sean drew three input NURBS curves; he selected the *Curve* function in the Rhino toolbar and clicked on screen to add control points within the 3D space. As explained, the control points determine the shape of the curves. He then used the *Loft* command to create a surface through his three curves, which then came to define the surface shape. Lofting is a technique in digital designs software for generating a high number of successive curves to form a surface from initial input curves, in the case of Rhino a high number of successive NURBS curves. The resulting surface was matched within the white cubic outline of a single EPS block in the Rhino viewport (fig 4.6). After lofting the three curves into a NURBS surface, control points along this surface allowed Sean to change the geometry by grabbing and dragging them to depress or lift a point which would recast the whole within the bloc. After each change the geometry adjusted slightly on screen as approximations from NURBS to Bézier curves were running in parallel in the Grasshopper script.

I asked Sean to tell me what he was doing, and he began explaining: 'Just doing some single block designs…' he was pointing to the screen, where the curving surface was fitted within the EPS block provided by the workflow, 'we are trying to test out a few things, for example when the blade shifts from negative to positive.' During test cuts, the team had identified an issue with control of the blade once its curvature shifted from convex to concave or the other way around. They wanted to examine this in more detail during the workshop. I commented that the curves on the screen did

not seem particularly challenging, Sean looked up enthusiastically: ‘You want me to break this? The thing is, I know this now. I understand what would work and what would not, so I do not really go beyond what is doable. I have been in these meetings before.’

I had been in the same meetings but had not developed this inherent understanding of the limitations of the workflow; I suggested we tried to do a cresting wave within the single block design, and Sean patiently explained to me why this would not be possible. To cut designs in EPS, the robots need continuously ordered input curves to determine the shape of the blade as the block moves through it. The workflow orders the curves along the y-axis of the design space to accommodate the needs of robotic fabrication meaning that it is not possible to do a reverse cut to free the negative space under a breaking wave by running the block backwards. To demonstrate Sean created the breaking wave form: ‘but if I just untoggled this…’ he said while clicking on some of the boxes in Grasshopper, suddenly the white box simulating the EPS block disappeared from view in Rhino: ‘Oh! You’ve broken it!’ he exclaimed gleefully. Morten leaned over from his own screen to see what we were up to.

Morten and Sean discussed how the script ordered input curves for the cut, while Sean clicked through the different boxes in Grasshopper looking for an error in the script. After satisfying himself that the Grasshopper script did not present any errors, he moved his attention to the Rhino viewports to begin realigning the surface curves, sliding them across the y-axis to position them successively until suddenly, the white box appeared again: ‘There it is! That is quite nice.’

Having satisfied my curiosity, Sean began moving the input curves around to test design approximation on the single block cut. During this work he continuously moved his design in the Rhino viewports, constantly zooming in and out to understand specific details of the design and how the approximated surface intersected the 3D shape of the block. At this stage he had no visual focus on the Grasshopper script, which was running in the background, but was moving, testing,

and viewing design iterations in Rhino in rapid succession while we were chatting about the designs and how they were going to test the robotic setup.

Morten leaned over from time to time to discuss robot-movements and what specific designs might mean for the cut. This went on for some time, other people from the Digital Factory team added their perspective while walking by. One of the robotics experts noticed a specific design and exclaimed: ‘This is a blade-executioner!’ before moving on. He was referring to stresses put on the metal blade by too acute angles in designs, Morten explained. In these cases the blade could deform or snap in two, as several had during prior workshops.

This points to an area where digital boundaries for approximation meet material counterparts created by the robotic fabrication setup. 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 elastic curves for the metal blade are mathematically precise and controllable; exceed this range, by having too acute an angle for example and numerical control becomes imprecise. Another boundary condition relates to the blade itself and outer limits of its flexibility in case it breaks. Boundary conditions also describe the 3D space in which the three robots in the setup can work together without errors such as collisions.

Most of these boundary conditions are encoded in the design and computation workflow to give architects fast feedback on the possibilities of their designs. In this way, the Digital Factory workflow not only ensure that designs fit within the boundary conditions of the fabrication setup, but the conditions themselves become generative of creative designs. I suggested this to Sean bringing up his comment about knowing the limits of the system. He agreed: ‘The question is: is

this design coming from me or from the machine? This is a grey area, we tell them what to do, but then they interpret it, right?'

I argue that this distribution of agency between designer and software is mediated by the digital materiality of the workflow itself. The complex set of mathematical and physical conditions that are inherent in the workflow both constrained and enabled Sean's creative work. Real-time feedback, enabled by clever mathematics, scripts and computing power, allowed Sean to work out ideas in an explorative manner while computations running underneath updated the geometry. High speed and precision invites fast exploration of the space between freeform design and production-ready geometry, and with time this lodges as an intuitive understanding of the limits of the system.

4.4 Digital materiality

Bladerunner and Digital Factory intervene directly in quintessential materials of contemporary architecture. On one side we find usual suspects such as concrete, rebar, and cement. Today, after water, concrete it the most consumed substance on earth (UNEP 2010), and while reading this, chances are more likely than not that you are only a few inches away from concrete in some form or other. Whether in slabs, beams or floors, concrete is probably to be found in the superstructure of the building you are in. No wonder, then, that innovative designers, engineers, and investors set their eyes on bridging the gap between design and fabrication in concrete formwork.

Digital materiality and computational design thinking

It is the argument of this thesis that Digital Factory, and architecture more widely, is also critically reliant on a form of digital materiality whose reach might well prove to be wider than concrete, even though its history in architecture and construction is much shorter (see Ch. 5).

Unlike concrete, whose unique molecular properties have shaped architecture for millennia, the materiality of computers have only had about six decades to make their presence felt, yet have done so with accelerating force. Exponentially growing in strength and reach, their powers extend beyond the molecular to also include the informational. And as we have seen, the informational is mediated by successive layers of mathematics, code, and software (see also Blanchette 2011).

Digital materiality emerges in the interplay between people, screens, design software, their algorithms, models, scripts and geometric primitives as well as their situations of use. Just as molecular materials come to transform action upon material objects, so digital materiality come to enable and transform architect's creative and collaborative practices on computers. We have already seen examples of this in the approximation algorithms of Digital Factory and Sean's fluid engagement with its design-to-fabrication workflow.

The notion of digital materiality is not new in architecture theory, but earlier conceptions differ in goals and scope from what I seek to develop here. In 2008, architects Fabio Gramazio and Matthias Kohler, leaders of the influential Robotic Fabrication Laboratory at ETH Zurich, defined the term in this way:

> We use the term *digital materiality* to describe an emergent transformation in the expression of architecture. Materiality is increasingly being enriched with digital characteristics, which substantially affect architecture's physis. *Digital materiality* evolves though the interplay between digital and material processes in design and construction. (Gramazio & Kohler 2008:7, emphasis in original)

Gramazio and Kohler use the term to describe the integration of fabrication constraints and programming in the design processes. This marks a shift in focus, they write, from the design of objects to the computational design of processes that will bring these objects into being; the same convergence of design and fabrication, which Digital Factory is also positioned within. This conception of digital materiality is not preoccupied solely with the design process. Gramazio and

Kohler also write that digital materiality bridges the worlds of material properties and digital logics, but do not expand on how these digital logics come to influence design.

Architects Achim Menges and Sean Ahlquist (2011:16) have advanced the concept of *computational design thinking* to describe design practice, which is oriented towards constructing computational systems leveraging clearly defined parameters and associative logics to explore the limits of technics and form. They propose that a deep understanding of how these systems operate, as form and as mathematical ordering constructs, is fundamental to computational design thinking. In these practices 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 not exhaustive descriptions of final forms themselves.

Gramazio and Kohler and Menges and Ahlquist are pioneers in digital design and fabrication. Their work highlights how a shift from finished object to processes, from free-form design to rule-based exploration, is at the heart of much digital design today. But from within this approach it remains unclear how imagination and creativity emerge in computational design. I seek to answer this question through my own conception of digital materiality, shifting the focus from how molecular materials or mathematical logics become the object of computational design to also discuss how the mediation of specific geometric primitives, scripts, models and software come to enable creative and collaborative agency for architects. How design practice, institutions and technology entwine to form a rich environment for extension of mind.

Material Engagement Theory and Material agency

In his 2013 book *How Things Shape the Mind*, cognitive archaeologist Lambros Malafouris describes the aim of Material Engagement Theory as being: ‘to restate the problem of the

interaction between cognition and material culture in a more productive manner by placing it upon a new relational ontological foundation.' (Malafouris 2013:35)

Material Engagement Theory, or MET for short, champions a relational approach to thinking and doing (see p. 31). What this means is that human creative thinking becomes a fundamentally situated activity where mind emerges through dynamic interactions of bodies, materials, and symbols and can never be the property of any of these elements alone. As already intuited by Gramazio, Kohler, Menges and Ahlquist, our creative imagination is bound up in interaction with systems reaching across material and informational realms (Blanchette 2011). It is the argument of this thesis that if we want to understand architects designing with the Digital Factory workflow, or any other digital design environment, we have to understand how mathematical, computational, and technical configurations of these environments come to shape creative extension of mind.

MET collapses hard distinctions between internal and external cognitive processes and forwards a relational perspective on agency. Malafouris sums up this perspective:

> If there is such a thing as human agency, then there is material agency; there is no way human and material agency can be disentangled. Or else, while agency and intentionality may not be properties of things, they are not properties of humans either; they are properties of material engagement. (Malafouris 2013:119)

In this view, agency is the relational and emergent product of material engagement. It is not something given to humans but something to be realised as humans interact with the materials of the world. The important question for Malafouris is not 'what is agency?', but rather 'when and how is agency constituted and manifest in the world?' (Malafouris 2013:147)

Malafouris (2014) puts forward the analogy of a potter at the wheel to explain how creative agency emerges from the interactions between matter, body, and mind. The potter cannot simply create a pot from an initial mental image of it; the wet clay will resist and transform the potter's

actions on it, and the potter has to feel and follow the clay as the pot emerges through this dynamic transaction. The same goes for mind and agency; cognition is in constant motion, it is not just the pot that is emerging and undergoing continuous change at the potter's wheel, but also the potter's creative and cognitive abilities (ibid. 145). MET seeks to restore dynamic life and potentiality to all materials and alerts us to the fact that the creation of form is not a question of abstract ideas being imposed on inert matter; rather it is one of form and ideas emerging through continuous and lively interaction. I argue that this relational process can be translated to the digital realm through the concept of digital materiality.

Advancing our understanding of computational design thinking in light of MET suggests that computational design thinking does not arise from manipulation of mental plans and representations based in abstract computational logics, but rather emerges from within the complex interplay of forces in a given digital design environment. The creation of form through digital design requires an understanding of how computational systems 'as form and as mathematical ordering constructs' operate (Menges and Ahlquist 2011), and how this 'bridges the worlds of material properties and digital logics' (Gramazio & Kohler 2008). Following the relational conception of mind and agency advanced here, this understanding is embodied, practical and historical; it is made possible by the establishment of technical and social environments for design research such as that carried out by Sean working through the single block design using the Digital Factory setup. Digital materiality seeks to capture this domain of possibilities while advancing a framework for analysing the entwining of creative agency, social mind and digital technics.

Material agency in digital design: the digital potter

An implicit claim from MET is that we use material and conceptual tools to recast abstract problems into more meaningful and manageable terms. At the core of the Digital Factory project is

a number of highly advanced material and informational problems: the description, control, and limits of elastic curves; the approximation of NURBS curves into Bezier and elastic curves; the data structure required for mapping 3D designs onto EPS blocks to determine cuts; the behaviour of the metal blade; coordinating robot movements, and interfacing with their control code.

To solve these problems in a way that allows non-experts to create designs that fit within their boundary conditions, the Digital Factory team have recast problems from abstract mathematics and complex 3D movements of robots and blade into something more manageable. Something giving designers such as Sean a handle on the constraints presented by robotic fabrication while allowing them to explore impacts of these along aesthetic lines.

The outlined workflow, permitting relatively intuitive design for robotic fabrication, is the result of more than five years of research and development mixing insights from advanced mathematics, robotics and engineering, materials science, computer science, architecture, and ongoing design research. The results of this process are 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. As we saw with Sean alternating attention between the Rhino viewports and underlying Grasshopper script to configure the creative possibilities of his own work, 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 while ignoring others (see also Cross 2006:37; Kallinikos 2005:189).

Due to the near instantaneous feedback between input geometry and approximated output, the design workflow lends itself to explorative discovery not dissimilar to the creative process of pot-making put forward by Malafouris. Let us return to Sean working out single block designs. Starting from an initial input, Sean used his mouse to turn, drag and shape on-screen geometry to see approximated formwork unfold in front of him in the Rhino viewport. Through this he discovered

the possibilities inherent in the modelling environment, and as he said, when I suggested creating a cresting wave that the setup would not be able to produce, he understands what will work and what will not intuitively based on his past experience working with the setup. Much like the potter at the wheel, Sean has built up an intuitive understanding for the materiality of his medium, though this is digital as well as physical.

My description therefore points to a formal complexity inherent in digital design, which some might argue sets it apart from pot-making. As we have seen in the Digital Factory workshop, digital design research can be a pain-staking process, which at times seems anything but fluid. Working on the code, testing it, failing, getting used to that failure, joking about it together, these are all part of using tools to make tools in digital architecture. But, I would caution against the idea that pot-making is not similarly fraught with possibilities for failure and not vitally dependent on the pot-maker building up experience with the materiality of clay. Both digital design and pot-making require skilful engagement with the possibilities and constraints of their respective medium, and this skilful engagement is borne from dynamic and explorative interactions with its inherent materiality. Mastery of this material engagement facilitates creative extension of mind. While I had been part of much the same meetings and workshops as Sean, I had never designed with the workflow and lacked the architect's intuitive understanding of the possibilities and limits of the workflow. When discussing this with Morten and Kenn, they both acknowledged that they had developed an intuitive understanding for the constraints of the Digital Factory workflow with time, but also emphasised that the variable approximation of NURBS input to Bezier or elastic curves means that design work takes the form of continuous exploration rather than straightforward transfer of preconceived ideas to the modelling environment. While approximations between input and output curves are often close with little variation between them, they sometimes vary, and in extreme cases return surprising shapes out of line with the input. Watching Sean play around with

these possibilities at the Digital Factory workshop, it becomes clear that even a highly systematic art, such as computational design, relies on interactive and fluid engagement born from minute interactions rather than relying exclusively on any detailed master plan (see also Parme 2018, Houdart and Minato 2009, Yaneva 2009a, Suchman 2006).

In my observations of Sean, he alternated between basic discovery involving periods of high activity with mouse and screen, continuously dragging and changing curvature to see what happens; these were interrupted by shorter periods for contemplation, where continuous movement and rotation of the on-screen block helped build a deeper understanding of the 3D impact of a given approximation. This in turn set Sean up for more deliberate movement of curves. Sometimes these explorations went astray, the mathematical algorithms running the approximation returned uncuttable and loopy geometry and he would undo the past couple of steps with a few keystrokes to try with a different approach. Alternatively, he incorporated the accident into his design. As in the example of the potter at the wheel, the relational emergence of form and ideas happen in ongoing transactions between designer and design environment. This adds a digital dimension to the enactive analysis of MET, and we can begin to see how creative agency and opportunities reveal themselves in computational design thinking through rich engagement with digital materiality.

Conclusion to chapter

The concept of digital materiality describes the way successive layers of mathematics, code, and software come to shape creativity and collaboration in digital modelling at 3XN and GXN. The Digital Factory project shows how the mathematical encoding of geometry and curvature, and the configuration of software and scripts used for its manipulation, come to facilitate material agency

for architects. Just as clay and wheel come to transform the action of the potter, so digital materiality come to enable and transform the creative practices of architects at 3XN and GXN.

There is a narrative point to my somewhat detailed description of elastic curves, Bezier curves, DLL files, Rhino viewports, and Grasshopper scripts in this chapter – namely that I hope this descriptive thickness imparts a feeling of solidness and materiality to digital design environments, which otherwise might come to seem virtual and disembodied. By exploring this digital richness architects can engage fluidly across domains of on screen geometry and more comprehensive digital scripting.

I have used the framework of Material Engagement Theory to argue that creativity in digital modelling practice is a situated activity where mind emerges through dynamic interactions of bodies, materials, and technics and can never be the property of any of these elements alone. Malafouris (2013) has advanced the notion of material agency to describe how tools and materials mediate our possibilities for acting in the world. In this view, agency is the relational and emergent product of material engagement. With this in mind, I have argued that part of the success of digital design environments lies in the way they allow designers to selectively zoom in on, mix, and process some aspects of this while ignoring others. This notion of complexity at a humanly meaningful scale offers a starting point for understanding the cognitive powers added by computational design tools and will be further qualified by turning to other aspects of digital design practice at 3XN and GXN in the following chapters.

Chapter 5: Model

In the preceding chapter, I introduced the notion of complexity at a human meaningful scale as one aspect of the cognitive powers provided by digital design tools while arguing that humans have always relied on materials and technology to recast complex problems into more meaningful terms. In this chapter, I outline a history of digital design tools – with origins as diverse as early Roman Shipbuilding and modern French car making – to argue that digital design models represents the latest iteration of a this human trait. This history shows how human ingenuity have exploited the physical and digital materiality of different tools and software to face a growing complexity in design and construction. Today, there is no one size fits all design tool, but rather a series of digital environments and practices that embody key logics from this history of design and software.

Architects at 3XN and GXN use a number of software environments to create 3D models of buildings. The more complex of these models are developed and maintained by GXN's Digital Design section in collaboration with project leaders and architects in 3XN. I will develop the concept of *modelling platform* to describe the relational nature of digital models developed at 3XN and GXN. In this view, digital models become platforms in which certain components remain stable over time, while others vary and adapt. This balance between stability and flux enables architects to selectively mix, bring forth, or hide specific aspects of the model over time, thereby enabling integration of the many practices and elements required to make a building. To illustrate this, I discuss an instance of problem solving on a façade design for a new 3XN building while showing how the elements in the 3XN and GXN modelling platform work by bringing together different aspects of the history of design in a flexible digital environment.

To explain how this environment comes to enable the extension of mind in the studio, I turn to Edwin Hutchins' argument for *cognitive ecology* (2010, 2005, 2014), which posits that mind is essentially distributed into social, material, and technical environments, which come to anchor

specific inferences or blends of ideas, concepts, and elements. I argue that the 3XN and GXN modelling platform is a vital element of this cognitive ecology at the studio as its digital materiality helps make certain designs and practice stable in the midst of flux, thereby enabling complexity at a human meaningful scale for the architects.

5.1 Model, platform

'Basically, we have developed a platform now, which is incredibly helpful.' In early December 2016, four months into my internship at GXN, Morten was killing time by trying to explain to me how modelling worked on a large 3XN project. He elaborated:

> This platform allows us to do all sorts of things. If you want to draw walls you can draw walls. You can draw them 3D or 2D. If you add a door it knows its dimensions already. We just changed all the façade elements on [another project] in one day because the model was already in place! So, do not talk about software, but talk about platforms. Because people here are doing more than one thing with this – they are doing 3D and 2D – and it is all integrated.

Together with Kenn, Morten heads the GXN Digital Design section, and along with Kenn he mainly works with complex digital modelling on 3XN projects. I had walked past Morten's desk in 3XN's Project Development department and found him waiting for a delayed team meeting for one such project. As he explained, I scribbled notes.

The project in question was CUBE Berlin, a large crystalline building occupying Washington Platz by the Spree in Berlin's Mitte area. Completed in 2019, its 19.500 m2 office spaces neighbour Berlin Hauptbahnhof to the north and the Federal Chancellery and Tiergarten park to the south. The masterplan for Washington Platz defines the building to be a cubic body of 3x42,5 meters putting emphasis on its four facades to the surrounding city. The design answer to this masterplan is indeed cubic in form, but its four glass facades break up unevenly into crystalline surfaces which promise

lively reflections of the city around it (fig 5.1). The design was nominated for a World Architecture Festival 'Future Projects Award' in 2017.



Fig. 5.1. CUBE Berlin render. 3XN Architects completed 2019.

All sides of the building have their own distinct appearance. This kaleidoscopic effect is made from the distribution of 48 triangular surfaces across the building's sides. Morten elaborated on this marriage of visual complexity and rule-based geometry while explaining the project's use of several software environments:

> We use Revit. All the names relate to the larger structure, it automatically adds elements or fits [them] to scale. But we cannot do façade design in Revit, it will be way to slow. So, in competitions and some design development you use Rhino and at that stage you do not worry too much about whether this line meets that one exactly. It is not the level you are at. That comes later. To do this, we pull all our data from Rhino via Grasshopper and we use this as our logic engine to generate Revit models via Dynamo. This allows us to work with the best of two worlds at the studio.

Over the course of this chapter, I will develop the concept of digital *modelling platform* to unpack this explanation. The 3XN and GXN modelling platform incorporates several software,

mentioned by Morten: Rhino, Grasshopper, Revit and Dynamo. I will use the example of façade development for the CUBE Berlin project to analyse the details of this platform, focusing on what the software do and how they come together to enable different design practices at the studio

Developing the façade of the CUBE Berlin has been no mean feat. Project development had between two and seven 3XN architects working full-time on the Cube in the 15 months I was at the studio, at times more. Morten himself spent a considerable amount of his time supporting this work. I often came by his desk to chat to find him be deeply engaged with some new scripting or modelling task as construction details for the façade evolved. As Morten explained to me, creating a structured modelling environment was crucial for project development on the CUBE building, why will become evident below. To explore the structure of this modelling environment, I take up the thread from Chapter 4 by examining how the digital materiality of different software environments are brought together in digital models to enable a multiplicity of design practices[14].

Morten's initial explanation leaves us some pointers to go by for understanding digital modelling at 3XN and GXN: 'Do not talk about software, talk about platforms.' In other words, try to understand how digital models become platforms that allow architects at the studio to integrate diverse design practices into a functioning whole.

So what is a platform? In a paper on the architecture of platforms for Harvard Business School, economist Carliss Baldwin and systems engineer C. Jason Woodard (2008) define platforms as:

> Modularizations of complex systems in which certain components (the platform itself) remain stable, while others (the complements) are encouraged to vary in cross-section or over time. Among the most stable elements in a platform architecture are the modular interfaces that mediate between the platform and its complements. These interfaces are even more stable than the interior core of the platform, thus control over the interfaces amounts to control over the platform and its evolution. (Baldwin and Woodard 2008:2)

[14] The collaborative aspects of these practices will be further elaborated in Section III of the thesis.

In the 3XN and GXN modelling platform, the stable components are made from the data structures and scripts that allow a model to work across different software environments. Variable complements depend on individual projects and are shaped by the specific designs, problems, and collaborators involved in these projects. I will discuss an instance of problem solving on the CUBE Berlin façade to illustrate the make-up and flexibility of the 3XN and GXN modelling platform while showing how elements in the platform work by integrating different aspects the history of design and software in a flexible digital environment. As I will show, this history is instructive for framing the arguments in this chapter.

5.2. Modelling history: drawing, drafting, devising, designating

Architecture, digital or otherwise, is preoccupied with design, a word that covers diverse meanings in relation to digital modelling practice. Etymologically, the word *design* is derived from the Latin prefix *de-* and verb *signare*, meaning to mark out, devise, choose, designate, appoint, or sign. During the Renaissance, the 16th century Italian verb *disegnare* took on the meaning of contriving, plotting, and intending, as well as drawing. This made sense for establishing architecture as a discipline primarily concerned with the intellectual work of design and subsequent drafting of production drawings for builders. French lifted both these meanings of the word disegnare from the Italian and passed them on to English, which uses design in all these senses today. (Terzidis 2007, Belardi 2014:10-11) *Drawing*, *drafting*, *devising*, *designating*, all these meanings of the word design form part of digital modelling practices in the studio of 3XN and GXN. A brief overview of the history of digital design and modelling tools will show how these differences in meaning have been encapsulated in different software environments, and how these differences come to inform the 3XN and GXN modelling platform today.

Drawing: lines on paper

Think about the architect at work and chances are you are thinking about the architect drawing. Drawing has been the official tool of architecture since the Italian Renaissance when Leon Battista Alberti made the case that architects should be designers, not makers (Carpo 2011). To this end, he defined a modern notational system of scaled architectural drawings in plan and elevation which could inform the creation of construction documents conveying design intent to builders at separate sites. A physical distance, which architecture historian Mario Carpo (ibid. 15) points out, went hand-in-hand with a growing estrangement between architect and builder that still influence the industry today.

Between the 1470s and 1970s architectural drawing was carried out on paper with the help of a number of tools, prominently among them the straightedge for line segments and the compass for arcs. These tools incorporated the shape of the geometric primitive forms that were adapted from Euclid to make up architecture's notation systems (Mitchell 2003:110, Kolarevic 2003:21). For more than 500 years, this kind of drawing remained analogue, reliant on the direct transfer between architect, tools, materials, and surface.

Imagine for a second a young child drawing a house on a blank sheet of paper. The child can start anywhere and might chose to do so with two meticulously drawn lines forming a upside-down v; a roof. From this follows the concentrated tracking of lines down either side of the roofs end-points; walls and the building's structure holding the roof in place. And these lines are followed by the addition of yet more lines forming a rectangular form for a door and a few smaller squares for windows. While 300 years and decades of skilled training separates the 18th century draughtsman and the child, the inherent logic of their drawings remains the same. This logic is *additive*: drawing add lines to paper to create the finished result – a building, a plan, a section, or a detail.

The classic architectural drawing is an additive process where form and intricacy is achieved through the addition of traces to paper. Lines are added to a drawing until a building appears from the aggregation. The drawing process excludes physical aspects of the world that might shape the form of the building, and the internal consistency of the drawing is not guaranteed by the medium itself (Tedeshi 2015:16). This is in part why Renaissance architects such as Alberti fretted over the formalisation of a clearly defined notational system.

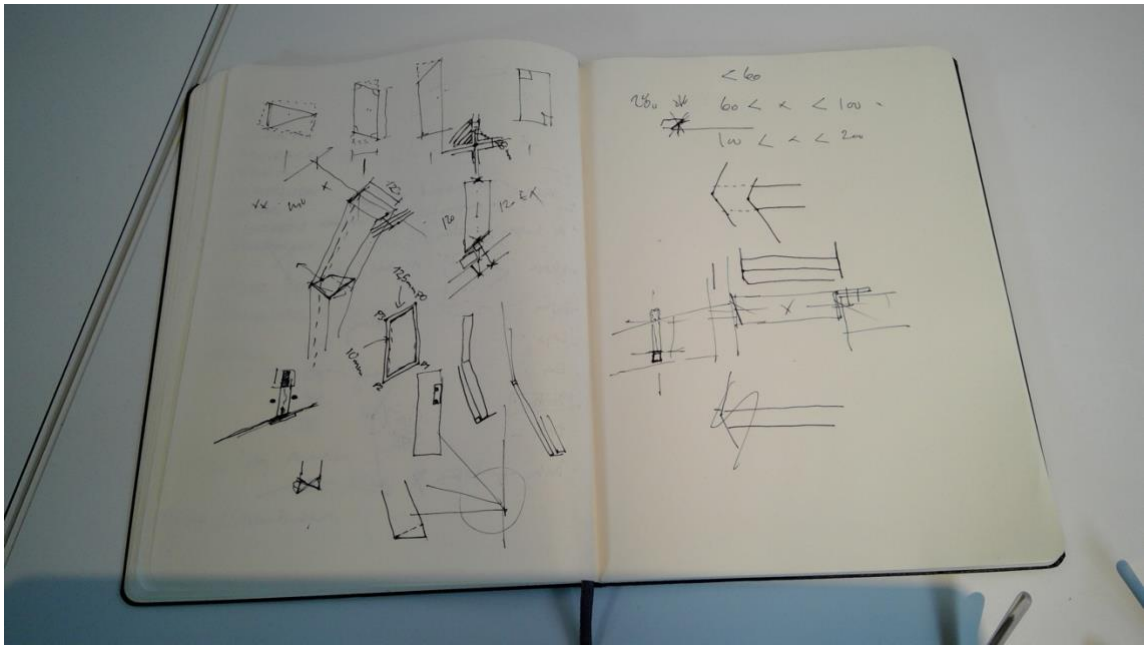

Fig 5.2 Sketches of profiles for façade elements for the CUBE Berlin project.

Today, architects at 3XN and GXN still sketch constantly to mark down or explore ideas. Speak to Anja, the 3XN office manager and you will find that she is supplying the office with a steady stream of tracing paper, A5 notebooks, high quality Japanese ink pens, colour markers and other utensils, which require constant replenishment. When I brought this up with Morten, he explained: 'sketching is often about helping each other understand basic elements, things such as basic profiles [for façade elements, fig 5.2], and here the drawing is still fantastic. But on the CUBE, drawings could not capture the full 3D complexity of the façade elements and fittings,' I will elaborate on this

below and here simply assure the reader that architects still draw; sketching is an indispensable tool at 3XN and GXN, but the kind of notational construction documents that preoccupied Renaissance masters have moved on to the computer.

Drafting: Computer Aided Design

In Chapter 4, I discussed the basics of a Computer Aided Design (CAD) system. Besides a graphical user interface for showing 2D and 3D graphics and input devices such as mouse and keyboard, CAD is dependent on digital methods for describing and manipulating geometry. This relies on a set of geometric primitives, basic shapes that are not derived from other shapes, as well as rules for transformation and logic for combination of shapes (Mitchell 2003). The functionality of a CAD system is described in this underlying coding of primitive shapes such as lines and curves and their geometric transformation, along with logic for their combination.

I discussed how NURBS, Non-Uniform Rational B-Splines, is one of the most widely used way of describing and controlling digital geometry today[15]. B-Spline is short for basis spline, a mathematical function describing the smooth curvature of a line segment. Graphically, the shape of a NURBS curve or surface can be adjusted by manipulating the placement and weight of offset control points that pull the curve or surface toward themselves. This intuitive interface allows designers to control NURBS geometry without having to worry about the underlying polynomial functions making it all work. Just as drawing tools, such as straightedge and compass have their own material logic that enables architects to create and manipulate certain forms, so does NURBS and the software relying on them. This relationship is integral to the concept of digital materiality as explored in Chapter 4.

[15] NURBS are as ubiquitous as pen and paper in contemporary architecture. Computer scientists Les Peigl and Wayne Tiller put it like this: “NURBS play a role in the CAD/CAM/CAE world similar to that of the English language in science and business: "Want to talk business? Learn to talk NURBS".” (Piegl and Tiller 1997:ix)

Designing with the material properties of splines can be traced back to first century AD Roman shipbuilding. The forerunners to splines were long pieces of pliable wood used in the creation of ship hulls. Perfected by the Venetians and popularised in England in the 1600s, splines utilised the material properties of wood to form physically optimal curves when bent. Desirable curves were held in place by a series of weights or 'ducks,' reminiscent of control points in today's digital splines; the ship's body could then be built around the splines. In early modern times, when ships had grown to considerable size, the laying out of splines for large hulls required vast spaces. Often, the only space available would be the lofts atop early modern shipyards, and the creation of a hull from a series of splines became known as lofting, which is the word still used for creating 3D surfaces from curves in digital design modelers today (Farin 2002:7).

Mathematical splines were first described in 1946, the same year the ENIAC computer was presented by John von Neumann to the University of Pennsylvania (Dyson 2012). Splines were defined by Romanian-American mathematician Isaac Schoenberg, a faculty member at the university. Schoenberg had worked with von Neumann as a mathematician at the US Army's Aberdeen Proving Ground where the ENIAC was developed, but it would be another 15 years before his work on splines came to be allied with the revolution in computers. The marriage of splines and computers was first achieved by French engineer Paul De Casteljeau in 1959, a young mathematician at Citroën who was not allowed to publish his results, and by Pierre Bézier an engineer at Renault shortly after[16]. The futuristic design and mass-production of cars at Citroën and Renault pushed these engineers to develop new ways of transferring the curving forms of models to accurate numerical descriptions for production.

[16] Not encumbered by corporate secrecy, Bézier's name became eponymous with Bézier curves the forerunner to NURBS, which we saw used as approximation tool by the mathematicians in the Digital Factory project described in Chapter 4 (see also Farin 2002).

Bézier and De Casteljeau came up with some of the earliest computer aided drafting systems whose basic mathematical and representational innovations still inform digital design today (Farin 2002, Poulsgaard and Malafouris 2017). They applied their ingenuity to the problem of production-line efficiency and developed CAD to optimise older processes of production drawing and draughtsmanship. This meant that their systems imported the additive logic at heart of analogue drawing processes, and this logic travelled from car-making to architecture when CAD was taken up at scale in the 1970s. According to architect Mark Burry (2011b:15) this focus on CAD as digital drafting still informs much use of computers in architecture today.

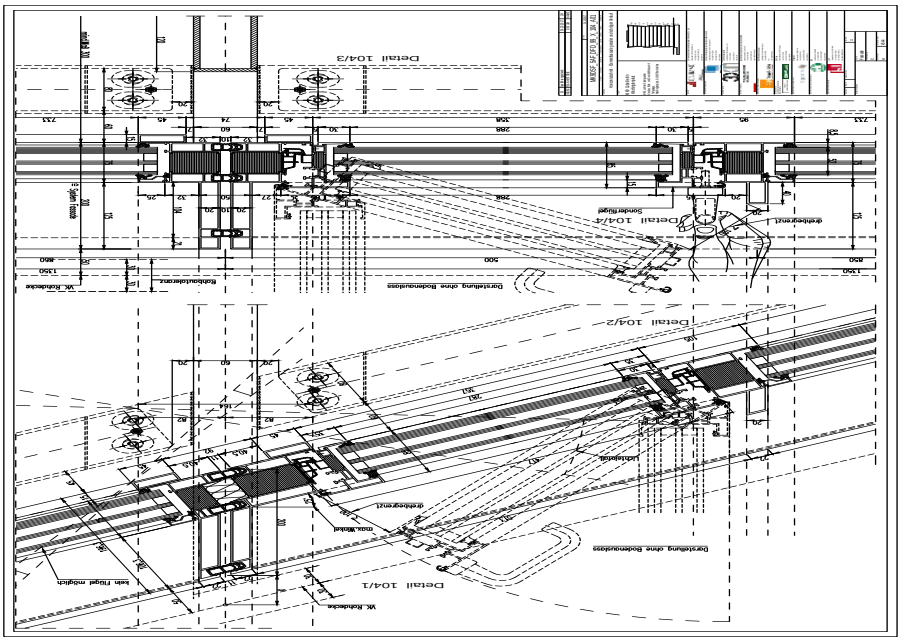

Fig 5.3 CUBE Berlin CAD drawings showing possible angles of fittings for glass panels from most extreme case to completely planar.

At 3XN, drafting remains essential for architecture projects. When we were discussing drafting techniques on the CUBE Berlin project, Morten explained how CAD drawings where used to show the domain of angles for the fittings of glass panels on the façade, from the most extreme case to completely planar (fig. 5.3), but also emphasised that these drawings lacked crucial 3D information

about the fitting of these panels. The additive logic of drawing, which was imported to the digital realm with early CAD systems, still informs modelling practice at 3XN and GXN today. But this is not the whole story. The core of the modelling platform at the studio relies on another innovative approach to computer aided design, which took form during the 1960s, one that sought to leverage the powers of computation to devise a new programme for design.

Devising: parametric design

Before 1946 'computer' was a job description. Computation was carried out by people, almost exclusively women, equipped with computation sheets and organised in rows that formalised the step by step execution of algorithms (Dyson 2012). Schoenberg, whose 1946 work on mathematical splines would come to transform computer graphics, had been with von Neuman at the US Army's Aberdeen Proving Ground during 1941-43 helping organise analogue computation work. The war required bombs and firing tables and developing these weapons required computation on a grand scale. During the war years von Neuman and others realised that digital computers could drastically lower the time and cost of this work. The ENIAC was developed at Aberdeen to calculate firing tables and its first program was a feasibility study for the nuclear bomb (ibid.).

The digitisation of computation facilitated an explosion in calculation capacity, which subsequently enabled new approaches to architecture and design. In the early 1960s a young software engineer at MIT named Ivan Sutherland (2003[1963]) wanted to revolutionise human computer interaction by creating the first interactive CAD program. The program, which he developed as his doctoral thesis, was called Sketchpad. Sketchpad is one of the earliest predecessors to the graphical user interfaces which are ubiquitous today and Sutherland received the Turing Award in 1988 for its development.

Back in 1963, Sutherland made it clear that drawings made with Sketchpad were: 'entirely different from the trail of carbon left on a piece of paper,' since not only the information that gave the drawing its particular appearance was stored in the computer, but also information about how the drawing was tied together which would allow it to keep its internal consistency during transformation (Sutherland 2003[1963]:25). Having completed a drawing with Sketchpad, the designer was able to then move and change its interconnected elements. Architect Daniel Davis (2013a), explains why this shift from drawing to relations within the drawing marked a revolution in digital design:

> Sketchpad offered a new way to explore *parametric* equations … designers could explore variations by modifying parameters and having Sketchpad automatically recalculate and redraw the geometry. But in Sketchpad designers were also free to modify the relationships of the model, which would also cause the recalculation and redrawing of geometry. Thus the architect's control of Sketchpad, as with most parametric modelling software, is not only through the parameters of the model but also through the model's underlying relationships. (Davis 2013a my emphasis)

The keyword here is *parametric*. Parametric design works by establishing points in 3D space before declaring mathematical associations between these to generate geometry. Once the model has been devised it can be used for endless variations through the manipulation of the linked parameters. A parametric model requires the explicit definition of relationships between parameters within the model. Once these are stated, changes to the parameters or their relationships will change the geometry of the model. In this way, a parametric model becomes an environment for the continuous computation of form, rather than a notational description of a single form. In digital design this ability more fully utilises the power of mathematical splines as the underlying polynomial functions deal well with continuous calculation of lines and curves (Carpo 2011:40).

In architecture, this curvilinear continuity was popularised in the 1990s through the work of philosopher Gilles Deleuze, whose discussions of morphology, folds, and topology caught the attention of a new group of digital designers. At the core of Deleuze's (1988) work on the fold is a

logic of continuous variation resting on parametric functions. Its presentation as a program for continental philosophy did much to popularise parametric functions within architecture, as Carpo dryly notes: 'Without Deleuze's timely mediation, few architects would have found high school calculus so highly inspiring.' (Carpo 2011:40) Architect Greg Lynn's 1993 essay on "Architectural Curvilinearity" is widely recognised as a key text in a new topological approach to design through parametric computation, and the 1990s saw an explosion of curves, folds, topologies, and blobs in architecture (see Carpo 2012).

The rise of curvilinearity in architecture is a result of what I have called digital materiality. It was powered by a newly possible combination of mathematical splines, the explosion in computation power, and the development of interactive graphical user interfaces for manipulation of form. The logic inherent in this new practice used computers to break away from the additive logic of drawing and drafting, which had been in place since the Renaissance. Instead, parametric equations rely on explicit description of relationships between elements, thereby introducing an *associative* logic into the creation of form (Tedeschi 2015:25; Kolarevic 2003:25). Rather than drawing a house from the top down, so to speak, by adding roof, walls, doors, and windows, parametric design software lets architects describe formulas for the relationships between walls, the size of doors, and the distance in-between windows and then explore the possibilities offered by these relationships.

In the studio of 3XN and GXN this associative logic becomes absolutely key to the modelling platform. Morten explained how the parametric model for the CUBE façade allowed the team to manage subdivisions of the 48 planar surfaces making up the façade into 774 smaller glass sections needed for its construction, keeping track of some 5.000 panels in total (fig 5.4). The explicit work with geometry as data means that digitally-minded architects not only have new powers to create and control complex geometry, but also new data-driven interfaces for managing building details.

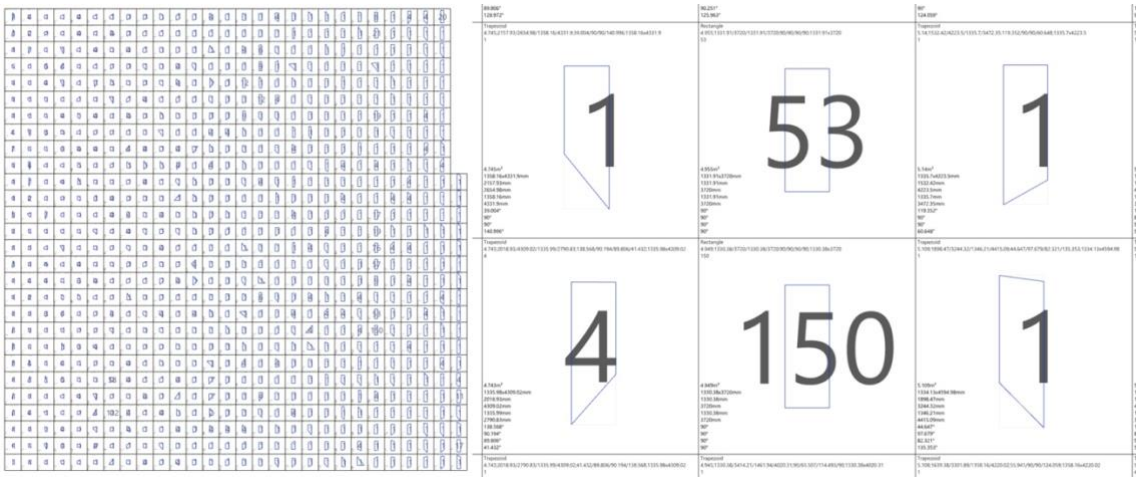

Fig 5.4 Representation of parametric data from the CUBE Berlin façade model.
To the right an overview of the shape and numbers of the 774 different glass panels.
To the left a zoom in on a section of these, showing dimensions and number of panels.

Designating: Building Information Modelling

The idea of Building Information Modelling (BIM) was first introduced into architecture by computer scientist Charles Eastman in 1974. In a whitepaper, Eastman (1974:5) pointed to the many inherent weaknesses of architectural drawings. They were redundant and inefficient, Eastman wrote, since they had to describe the same part of a building at several different scales. They were hard to keep consistent and up to date; if one drawing changed, a whole set of related drawings had to do so as well. Often this did not happen in a consistent way, leaving architects and builders in the lurch and forced to make decisions based on obsolete information. In short, drawing was not an efficient way of maintaining building information and structuring the relationship between architects and builders.

BIM was introduced to leverage the power of computers for an efficient system for describing a building between the many collaborators involved in its construction. BIM approaches the problem as a question of how to maintain the integrity of information throughout the building lifecycle. Unlike computer aided drafting in CAD, which simply allowed documentation to be drawn via the

computer, BIM links up parametric modelling with database capabilities. The goal is to create a single, unified model, which contain all the information needed to create a building. The logic of this type of modelling is not only associative but specifically that of the database. The logic of BIM is *object-oriented*, that is, it relies on the definition of classes of objects which can be manipulated and updated *en masse*. In BIM, architects designate elements of the building, such as walls, windows, or doors, to linked families in a database model. These families can be maintained and updated across the whole building. In the CUBE Berlin example, this means that integration of façade panels into families for each of the 48 planar surfaces making up the façade enabled efficient control as details such as fitting systems, types and thicknesses of glass were added (fig 5.5).

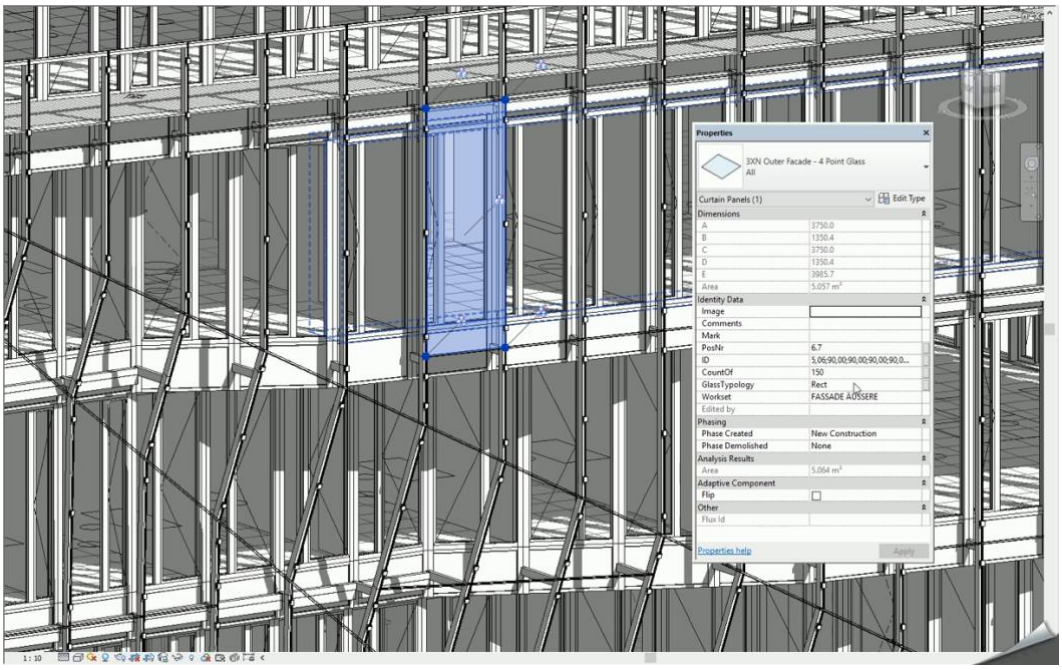

Fig. 5.5 Screenshot from Revit showing façade panel that is integrated into larger 'curtain wall' family for one of the 48 planar surfaces making up the façade design.

The benefits of a parametric design model tied to a relational database have proven to be incredibly valuable. BIM promises to provide project teams with the ability to digitally coordinate

collaboration prior to and during construction (Garber 2014, Garber 2017, Deutsch 2017), but integration between software environments remains challenging.

Interoperability and collaboration are therefore core concerns in Morten and Kenn's day-to-day work at 3XN and GXN. New modelling tools expand the quantity of information available in the design process, forcing them to develop practices for maintaining data quality and filtering between relevant and irrelevant information for the architects and their collaborators (see Ch. 8-9). The different software components in the modelling platform help them do this by encapsulating design practices – from drawing and drafting through to parametric modelling and object-based database maintenance. Working with structured data, exchanged via scripted interfaces between software, is crucial to the platform as its application in the design of the CUBE Berlin façade will show.

5.3 Digital modelling at 3XN and GXN

Work at 3XN and GXN relies on the different meanings of the word design as they are encapsulated by architectural software in the modelling platform. Inspired by MET, one of my central arguments is that humans have always relied on materials and objects to recast complex problems into more manageable terms. The historical outline above shows how architects have exploited the digital materiality of different mathematical constructs and software configurations to face a growing complexity in design and building (see also Poulsgaard and Malafouris 2017). An example from the CUBE Berlin project can illustrate how this plays out at 3XN and GXN, while further defining the modelling platform and its role for creative extension of mind in the studio.

Model platform

In spring 2017, following a number of chats since our first discussion of the CUBE Berlin project, Morten sent me a digital sketch he had made of the project's modelling platform:

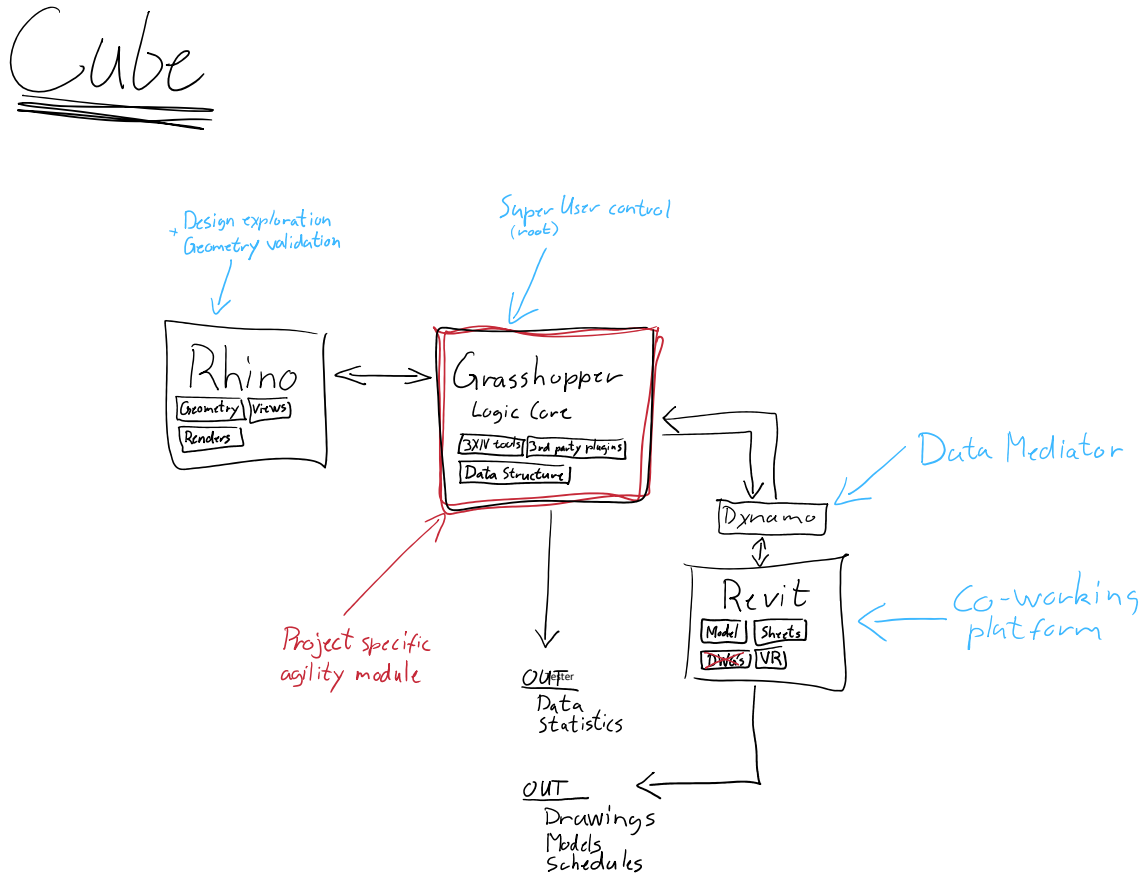

Fig. 5.6 'Rhino and Revit and some hacky stuff in between.'
Morten's sketch of the CUBE Berlin modelling platform.

'It is basically Rhino and Revit and some hacky stuff in between,' he said when explaining the platform to me. During the conferences Morten, Kenn and I were presenting at in 2017-18, we could see that leading European architecture studios were developing and fine tuning similar setups. In October 2017, Morten and I sat down for a recorded interview to talk about his sketch and this 'hacky stuff in between'.

Design exploration: Rhino

'We have our Rhino and what we mainly use this for is control of geometry,' Morten started out explaining. Rhino, made by Robert McNeel & Associates, is 3D modeler and CAD software used for creating and sharing 3D models in architecture. Rhino geometry is based on NURBS, giving users a simple interface for drawing freeform curves, surfaces, and volumes. Creating a form can be done with a few drags of a mouse using the software's basic functions, and manipulating form can be done fairly intuitively using the NURBS-based control points connected to lines and surfaces.

Rhino is the favoured software at 3XN and GXN for creating, manipulating and evaluating designs from a geometric point of view. It is *the* software in 3XN's Competition Department, where fast creation and evaluation of design concepts is paramount (Ch. 8). On geometrically complex projects, Rhino remains in use for geometry validation during project development, for example to evaluate how results of localised construction detailing impact the overall design of a building (see below and Ch. 8-9). Rhino is an open-ended software environment that supports the Rhinoscript and Python scripting languages. These scripting languages enable a system of plugin tools with additional functionalities created by both McNeel & Associates and individuals (Ch. 4).

Logic Core: Grasshopper

Grasshopper is a visual programming environment and parametric design plug-in for Rhino. It was commissioned by McNeel & Associates and released in 2007 as *Explicit History*. The name Explicit History was a question of 'does what it says on the tin,' since the plugin's core functionality is giving designers access not just to geometry but also to the history of how this geometry has been made via parametric relationships and functions.

Grasshopper enables the creation of visual scripts that express relations between parameters and user-defined functions for generating geometry. Scripts are created by dragging predefined and

custom-made components onto a visual canvas, where they are subsequently connected with wires to enable output from one component to become input for others. The clustering of components and connections can quickly become complex, giving messy Grasshopper scripts the industry nickname 'spaghetti' (see Davis 2010). Several digital designers at 3XN and GXN professed that it could be tricky to untangle others' programmes once these evolved from the most basic of functions (p. 249, 180, 175, 174).

At 3XN and GXN, Grasshopper is used for design exploration by individual architects during competitions; it is used to create scripts for managing difficult geometries by teams in both Competitions and Project Development (fig. 5.4); and for manipulating and managing geometry and data in research projects such as Digital Factory. Grasshopper's ability to explicitly define geometry as parametric functions and data, which can be structured, managed, and sent to other software environments, forms a core element in the modelling platform of 3XN and GXN. Morten explained:

> Grasshopper is the logic engine, this is the thing that calculates the whole show and allows us to extract data. It is integral to the workflow, if you want to change anything you have to go back to your logic engine. The whole process of linking and re-creating geometry is based on data, and that pipeline is automated as much as possible.

Data mediator: Dynamo

Dynamo is an open source graphical programming environment for the Revit BIM software developed by Autodesk, Inc.. Dynamo resembles Grasshopper in functionality and extends the capabilities for visual scripting and data handling to Building Information Modelling.
At 3XN and GXN, Dynamo is used to parse data from Rhino via Grasshopper to Revit in order to recreate Rhino geometries in Revit building information models. This usually happens once a project moves from the Competition department to Project Development (see below).

Co-working platform: Revit

Autodesk Revit is a Building Information Modelling (BIM) software that links 3D parametric models with a database for geometric and other design and construction information. Geometry in Revit is assigned an into families which are ordered using a database (fig. 5.5). As a result Revit does not support creation of freeform geometry with the same ease as Rhino. This makes dealing with form more cumbersome in Revit but it also makes team-based project management and construction detailing more manageable. By organising individual building elements into families, these can be updated in collaboration with partners such as engineers and manufacturers; once a change is made to one element in Revit the update will propagate to the whole model to keep all components consistent.

At 3XN and GXN Revit is used to manage and carry out many of the tasks required during project development, including project management, construction and design detailing, design of fabrication details, and drafting of construction drawings, planes, sections, and details to share with partners and builders. Geometry in Revit relies on up-front definition of elements and families. Once families are defined by a 3XN Project Development team, they serve as stable data repositories where information about elements, such as dimensions and materiality, can be updated in consistency with the overall building model. To recreate complex building designs in Revit, the GXN Digital Design section rely on Grasshopper, Dynamo, and custom scripts to parse data from Rhino and build families in the Revit building information model. Morten explained:

> It is a sort of deconstruct-reconstruct approach. We deconstruct all geometry [from Rhino] into data and then use this data to reconstruct it again [in Revit]. It hinges on data-exchange. We are working with data not geometry, the only geometry being transferred are the points and lines [used for the building grid], this is as far as we have reduced it when it comes to geometry.

Data structure as stable interface

In their introduction to platform architecture, Baldwin and Woodard (2008:2) define platforms as complex systems where certain components (the platform itself), remain stable, while others (its complements), vary. They specifically highlighted interfaces that mediate between platform and complements as the most stable elements so that control of these enable control of the platform.

In the 3XN and GXN modelling platform, control of the platform is predicated on what Morten called the logic core, the data structure and scripts that allow the diverse software utilised at the studio to work together. An instance of problem solving for the CUBE Berlin facade can illustrate how this setup helps anchor and make stable complex design operations at 3XN and GXN.

The CUBE Berlin puzzle

3XN secured the CUBE Berlin project in a high profile competition win in 2007. The project then went through several years of changes to the line-up of developers and investors before its present constellation was settled in 2015. The new developer group wanted to reopen the building's façade design. For half a year, a small team of 3XN architects revisited the proposal in Rhino to experiment with different design expressions within the central cuboid form. 'Basically asking, what it is possible to do within the confines of a cube,' Morten said, considering their work: 'they turned onto his crystalline form, with surfaces pulled in strategically to create these off-set triangular planes that reflect views of the city.' The developers liked it, and after the new design was settled, the CUBE Berlin moved to Project Development proper.

To enable project development and detailing of the façade in Revit, the team developed a shared 3D grid for all the digital models of the building. This served as the basis for a data structure created using Grasshopper where building elements could be identified based on their location in the grid. Along with Dynamo this logic core would enable the linking of geometry from Rhino to

Revit. The data structure and grid was developed to coincide with core tectonic and construction details so that these could be parametrically defined and locked into a rationalised construction system in the linked Rhino and Revit models[17]. This would allow the CUBE team full control of façade elements while developing construction details, which became crucial for the project.

Recall that the CUBE Berlin façade consists of 48 different surfaces distributed in combinations across its sides to achieve the building's kaleidoscopic effect. The NURBS-based modelling environment in Rhino made it simple to work with these surfaces during the CUBE Berlin competition and subsequent façade development. But once Project Development took over, modelling work around construction detailing was moved to Revit, which lacks the same simple geometry kernel. Once these large surfaces were exported to Revit's Building Information Model they had to be assigned to families, and the subdivision of the many smaller glass panels making up each surface had to be detailed in relation to the building's grid. Morten explained:

> Drawing the large surfaces and subdividing them in Revit required applying what is called a *curtain wall system*. This means telling Revit that each surface belongs to this family. But we have 48 surfaces, each would be its own family, and all would be subdivided into a total of 5.000 glass panels with a specific rotation in relation to the grid. If we wanted to make a change, let us say change the height of some of these, we would have to go into 48 different family types and change the parameters. Even small changes would have taken weeks!

Revit is a BIM software for managing families of objects during project development. This means that any geometry in a Revit model has to be defined as part of a predefined family of objects such as the *curtain wall system* mentioned by Morten. When coming up against the design intent of the architects, the limitations of the digital materiality of the Revit software for modelling complex geometry becomes evident.

[17] The 3D building grid defined during project development is a key structuring element in data driven design at 3XN and GXN. It provides a 3D coordinate system to locate elements in and across models, a rationalised system for aligning key structural details, as well as a data structure for organising and exchanging data about elements across different modelling software.

Subdivision of the surfaces into smaller glass panels was non-trivial for several reasons, Morten explained, including: that these would need to come in a large number different shapes to realise the design intent (fig 5.4); that as few shapes as possible was required to keep this cost-efficient; that there are material limitations for how acute the point of a triangular piece of manufactured glass can be; and that the subdivision of panels needed to take into account how to fit them at varying angles to the buildings construction system. This was not all, Morten elaborated:

> We defined the building grid thinking about the internal structure of the building and how to divide certain spaces. So there were demands to functionality and demands to the [façade] architecture and these demands had to meet in the space between the structure and facade. The complexity was not really in the form but in all these elements meeting in funky angles across the building. We could not really represent the full 3D aspects of this in plane and section.

In essence, this amounted to solving a vast 3D puzzle on the façade – all the while creating the pieces of the puzzle in order to solve it with as few different pieces as possible. The team used the parametric setup of Grasshopper to encode rules for subdivision, including minimum dimensions for panels, construction details for fitting the panels, and their parametric relations to the building grid; the geometric subdivision from 48 surfaces to 5.000 panels was optimised computationally in Grasshopper before panels were exported back to the Revit model and assigned to a shared family. These operations – design of the façade surfaces using Rhino, devising a script for subdivision and integration of face panels using Grasshopper, and designating and detailing panels in a family in Revit – utilise the different practices inherent in the linked software platform. ‘Instead of spending four years simply finding a solution for how to build this, we could have on person spend four months running through everything.’ Morten explained. The façade puzzle would have been incredibly time-consuming for the architects to solve without the model platform allowing them to anchor and mix relationships between geometry, software, and logic operations.

5.4 Model agency

In working out the façade for the CUBE Berlin project, the GXN Digital Design section were facing several interconnected problems, including: 1) parsimonious subdivision of 48 pieces of geometry from Rhino into façade panels; 2) description of 774 panels in a 3D building grid and data structure to allow parametric handling of all elements; 3) rationalisation of a construction system for the façade, which would match façade geometry, building, grid, and panels; and 4) precise integration of 5.000 glass panels with fittings at varying angles to the building grid. These types of interconnected aesthetic, data, and construction problems are the background to the platform approach described by Morten; the modelling platform helps architects solve these problems by anchoring cognitive ecologies that integrate a variety of practices in the studio.

The model platform co-constitute cognitive ecologies

Anthropologist Edwin Hutchins (1995a, 1995b, 2005, 2010, 2014) has introduced the notion of cognitive ecology (2010) to explain how the cognitive properties of teams and individuals come to be entangled with material, technical, and institutional environments. He argues that understanding cognitive processes requires systemic analysis of the tools and environments in which these processes operate. As an example he points to Gregory Bateson's (1987[1972]) *ecology of mind*, and Bateson's example of a blind man with a stick:

> Suppose I am a blind man, and I use a stick. I go tap, tap, tap. Where do I start? Is my mental system bounded at the handle of the stick? Is it bounded by my skin? Does it start halfway up the stick? Does it start at the tip of the stick? But these are nonsense questions. The stick is a pathway along which transforms of difference are being transmitted. The way to delineate the system is to draw the limiting line in such a way that you do not cut any of these pathways in ways which leave things inexplicable. (Bateson 1987[1972]:465)

With the concept of cognitive ecology, Hutchins expands the limiting line outwards from the individual so as not to exclude any pathways of high connectivity. In line with the concept of digital

materiality, I seek to develop in this thesis, Hutchins' goal is to redraw the boundaries of mind for a more comprehensive analysis of cognitive processes with their technical and social dimensions.

Hutchins is writing from the perspective of distributed cognition, but in a recent paper (2014), he highlights how this does not refer to a subset of cognitive processes happening under specific circumstances but rather is a feature of mind in general. Mind is never an individual phenomena but always distributed across social and technical environments (cf. Clark and Chalmers 1998). For Hutchins: 'the interesting questions concern the elements of the cognitive system, the relations among the elements, and how cognitive processes arise from interactions among those elements.' (Hutchins 2014:36) This approach can help explain the cognitive powers inherent in the platform approach to digital modelling at 3XN and GXN.

A cognitive ecology describes a bounded system of interacting elements enabling and anchoring human mind. In this vein, the digital modelling platform can be analysed as co-constitutive of a cognitive ecology encompassing code, models, and screens as well as the organisation of teams, projects, and departments in the 3XN and GXN studio (Ch. 9). The modelling platform connects different software environments through pathways of high informational connectivity, but it is not simply data and geometry that are transmitted but also different studio practices and logics from the history of design and software, which are blended into the model. For the CUBE project, Morten explained how these practices and logics included drawing of façade geometry in Rhino, devising the building grid and façade panels parametrically in Grasshopper, designating panels to the Curtain Wall family in Revit's object-oriented database, and drafting details for their construction in Revit.

The model platform anchors conceptual blending

Both Hutchins (2005) and Malafouris (2013:103) use the framework of *conceptual blending* to explain how mind integrates different practices and logics through material engagement.

Conceptual blending (Fauconnier and Turner 1998) refers to mappings in the conceptual system of a cognitive agent. In this, structures from two or more input spaces are selectively projected into a separate blended space which thereby develops emergent cognitive properties not available from the inputs. Fauconnier and Turner (1998:136) offer several examples, shortest of which is the sentence: 'They dug their own financial grave.' The meaning of this sentence emerges from two discordant input spaces – cemeteries and finance – into a third blended space with its own emergent structure that provides specific inferences.

Conceptual blending is routine activity. While Fauconnier and Turner operate in mental realms, Hutchins (2005) argues that blends often rely on material anchoring, externalisation of the blend in materials and tools that provide stability while removing cognitive load. As an example he forwards the act of queuing for theatre tickets. Queuing creates a spatial memory of the order of arrival of theatregoers. This spatial memory anchors a conceptual blend of a line segment (not a queue without sequence) and sequential order (not a queue without linearity):

> 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 2005:1562)

We can consider the digital model of the CUBE Berlin façade as a 'materially anchored' conceptual blend in this manner. Developing the model of the façade required input of conceptual logics from at least three separate spaces (and likely many more): freeform additive drawing (from Rhino), associative elements in 3D Cartesian coordinate systems (building grid and data structure), and object-oriented component data (Revit families). Elements such as cubic and crystalline geometry, building layout and grid, logic of data structures, and component materiality were all mapped onto digital relationships in the modelling platform.

From the emergent structure in the model, new inferences such as how to subdivide and detail 5.000 individual façade elements while maintaining the aesthetics and functionality of the wider building design becomes possible. The blends of geometry, data, construction system, and the physics of glass that enable these inferences were embedded in the digital materiality of different software environments such as NURBS geometry from Rhino, the data structure and scripts of Grasshopper, and component families in Revit.

Fauconnier and Turner (1998:135) highlight selective aspects of blending. In their example only parts of meaning or structure from the input spaces are integrated to create the blend, others are left out to make new inferences possible. In the case of the digital model for the CUBE Berlin façade, it is not entirely clear what is selectively blended and what is left out, as it is rather a case of all of the above elements being integrated into the modelling platform along a historical dimension. This happens in iterative steps – geometry, building grid, data-structure, subdivision, component families, specification of glass. Non-crucial information from the input spaces might be left out from step to step, but is retained in the explicit history of the parametric model.

Recall that Morten called Grasshopper the logic core of the modelling platform. Recall also that the original name of Grasshopper was Explicit History. As this name implies, the efficacy of the modelling platform lies in the way it allows architects control of series of blends and integrations by defining these parametrically. Grasshopper scripts work by performing operations on input to produce output which are selectively taken as input to new functions and so on. The associative logic of Grasshopper is conducive of conceptual blending by taking different input, geometry, data, scripts and turning them into a unified model. This layered sequence is anchored in the digital materiality of the software and works by allowing designers selective access to data and representations so that relevant combinations might be made visible at any one time[18].

[18] This juxtapositions layers and levels of complexity is shared with design sketching, which Nigel Cross (2006:37) argues allow architects to handle different levels of abstraction simultaneously by having these juxtaposed on the page

The model platform allows complexity at human meaningful scale

Hutchins describes material anchors for conceptual blends this way: ‘A mental space is blended with a material structure that is sufficiently immutable to hold the conceptual relationships fixed while other operations are performed.’ (Hutchins 2005:1562) For Malafouris (2013:104), conceptual blending is the crux of enactive signification, and the integration between symbolic and material input is what gives the material world its cognitive and affective efficacy. This anchoring and tying of symbolic and affective meaning to material patterns is at heart of the modelling platform of 3XN and GXN and its blending of conceptual and material structure may explain how digital design is constituted in material engagement.

The digital materiality of different software in the platform enable integration of divergent software logics and design practices throughout the history of a project such as CUBE Berlin. At any one time, the digital pathways between software in the modelling platform allow for different relationships in the model to be brought forth and explored by the architects. A panelised surface (not a façade without dimensions and materiality) and a dimensioned glass plate (not a façade without integration with a wider construction system) can be combined in an integrated façade model. Bringing penalisation, material concerns, and construction system together, the blend enables new inferences about the façade design. As different software remain coupled in the platform, the blend can be dissolved into its inputs – geometry, data-structure, glass elements – to be worked at individually and integrated again. This makes possible the integration of practices of drawing, drafting, devising, and designating which encapsulates logics from the multiple meanings inherent in the word design; they are additive (creating geometry during design exploration) associative (establishing building grid and data-exchanges), and object-oriented (elaborating on building elements and construction detailing). The explicit historical layering and blending of the

(see also introduction to section III). The Digital model enhances this ability by increasing capacity for information, adding new practices to the mix, as well as new interfaces for blending layers of complexity and abstraction.

results of these practices allow for constant realignment, shifts and integrations between emergent layers in the model. Part of the success of resulting modelling platform lies in its possibilities for *functional simplification*, that is the way it allows designers to selectively zoom in on, mix and process specific aspects through specialised practices.

Organisation and communications scholar Jannis Kallinikos (2005:189) argues that functional simplification works by demarcating an operational domain in which the complexity of the world is reconstructed as a simplified set of instrumental relations, it entails:

> the careful demarcation of an operational domain (i.e. the functionality of the program), the definition of the tasks that embody the functionality of the program and the lay out of the steps that have to be followed in order to accomplish a task or series of tasks. (ibid. 191)

In a shifting and contingent world, Kallinikos argues, technics come to produce platforms of manageable relations, models of a more complex reality. Functional simplification enables control through clearly demarcated practices, for example for the decomposition and exchange of building data between software environments. As in Baldwin and Woodaard (2008), the argument is that control within a software platform is predicated on management of key interfaces that mediate between platform and its complements.

In the case of the 3XN and GXN modelling platform, control of the interfaces for data-exchange allow the selective blending of different aspects of the larger model dependent on the problem at hand. This enabled the architects to work simultaneously with the same façade as either large planar surfaces, data points on a grid, detailed glass panels with physical dimensions, or as structural system. Shifting between these aspects permit research into dynamic and complex problems at a human meaningful scale. When working with geometry, the overall effect of operations on façade design can be gauged visually; working with the data structure enable a focus on logic operations and the subdivision and angled placement of 5.000 smaller panels, which would be impossible to carry out visually; detailing panels in linked families allow for detailing with little concern for the

fact that the 5.000 panels have to be fitted with very high precision to realise the original design intent in the finished building (fig. 5.7).



Fig. 5.7 CUBE Berlin upon completion in 2019, 3XN Architects.

Hutchins and Malafouris point to the fact that our creative lives – thinking, doing, and making – unfolds with material forces coming together to afford and constrain the cognitive opportunities available to us. With the concept of digital materiality, I argue that the internal configuration of software is a key material force in the 3XN and GXN studio, by showing how the modelling platform integrate different design practices and software logics in the course of an architecture project. I argue that creativity and mind at 3XN and GXN are not intracranial processes; they are, anchored in cognitive ecologies; they are constituted in these ecologies through the development of specific conceptual and material blends and practices, leading people to think about and do design in distinct ways simultaneously within the modelling platform (see also Ch. 8-9).

Conclusion to chapter

At 3XN and GXN, the digital modelling platform forms a dynamic environment for integrating a number of divergent design practices and logics into projects, utilising the digital materiality of different software environments. Digital models integrate the vast amounts of data that often underlie 3D form in architecture into computational systems where geometry translates to data, and data to geometry. This shared informational basis permit integration across a range of software environments allowing for modular combination of input and outputs from software, scripts, and models across all phases of architectural design and construction.

A brief historical overview of design and modelling showed that several design practice and software logics form part of this integration in the 3XN and GXN modelling platform: additive combinations of lines during sketching and drawing, devising of associative relationships during parametric design and data-exchange, and object-oriented control in designation of building elements to database families. In a sense, the modelling platform incorporates the history of digital design into its functional environment. This large scale historical integration is reflected in the smaller scale integration of input spaces within the time-frame of an individual project such as the CUBE Berlin. Using the framework of conceptual blending we saw how data exchange and dynamic interactions between input in the model made possible inferences whose formal and computational properties exceed what could be achieved by any one person or software environment.

Hutchins' framework of cognitive ecology showed modelling as a dynamic system of computational, aesthetic, and organisational factors interacting with each other. It seems the designing mind is distributed and emergent in digital modelling. Digital design thinking is empowered by the dynamics of specific modelling environments. Models, software, and digital materiality anchor blends of ideas, concepts, and practice, thereby enabling the extension of mind,

which becomes an emergent property of cognitive ecologies rather than inherent in the brain of the designer. This approach opens new venues for the study of digital technology in computational design modelling, and for thinking about the relationship between practice, innovation and change within the architectural professional community. It also begs the question of how architects develop skills to engage intuitively and fluidly with the many practices and possibilities that form part of this cognitive ecology. This will be the focus of the next chapter.

Chapter 6: Screen

Chapter 4 and 5 have discussed how architects' creative agency is inextricably mixed up with their digital models at 3XN and GXN. This raises questions about the possibilities for extension of mind via a medium that is radically different from drawing. Digital modelling introduces a level of formal complexity into design practice. Generating and working out ideas using models and scripts require a fine-grained understanding of the digital materiality of various software, and the possibilities and constraints they give rise to. How do architects at 3XN and GXN establish a sense of familiarity with these tools in order to work creatively with them in the larger context of architectural design projects? Answering this question requires shifting the focus outwards from the tools themselves to the relationship between tool and designer in the 3XN and GXN studio, first with a focus on perception of space and form in a potentially disorienting digital realm; then focusing on the concept of design research and how this helps architects build familiarity with their tools to enable creative extension of mind.

6.1 Entering The Grey Room

'Tools themselves are not exciting me anymore, what is important is how we can use them to add value to our projects,' Kasper said after one of our earliest meetings in 2016 as he, Lasse and I were having lunch in the large hall of the old gunboat shack at Kanonbådsvej. Our prior meeting had dragged on and the room was empty except for us. Kasper and Lasse were trying to help me think through ideas for how to approach digital design once I started working at the studio.

Kasper who had been messing around with his phone pushed it across the table to show a picture of a large architectural model covered in brown clay: 'This really blew me away,' he said. 'This' was Gehry Studio's *Ungapatchkey Pavilion* at the 2008 11th Venice Architectural Biennale. The

model had been part of the Masters of the Experiment exhibition in the Corderie, Venice's old rope factory at the Arsenale, which was showcasing front-runners in computational design. The structure on the small mobile screen resembled a larger than life architectural model built from timber and plywood to form Gehry's characteristic bending and cut surfaces. Most of the plywood had been covered in brown clay which was drying in a cracking and earthy pattern.

Kasper scrolled through his pictures to show the neighbouring exhibition, the *Lotus* by Zaha Hadid Architects, a sleek and sinuous structure of interweaving fiberglass tendrils forming part bench, part sculpture; a remarkable piece of mathematical and material engineering. In contrast to Gehry Studio's earth-bound experiment, the Lotus was wearing its computational origins on its sleeve. Standing next to each other in the Corderie, the two structures provided a moment for Kasper and Lasse to reflect on the intricacies of computational design. 'I used to measure GXN against the avant-garde in parametric design, but this is not the case anymore. We've become less interested in form, and more focused on how tools, materials and design can support specific values in our projects,' Kasper told me while flicking through pictures of the two sculptures. 'It can be hard to get a hold of this type of parametric geometry,' Lasse, who had been with Kasper in Venice, explained about the Lotus sculpture: 'it is coated in a completely smooth surface material. There is no material process. There is no patina, if you are unlucky with your material it might discolour, but that is all.' He continued:

> We know that there is a materiality to our tools and products when designing, but this materiality can be strangely absent in the 3D space on the computer. You sit there with your grey expanse, this grey room, and then what do you do? Sometimes, it seems, you end up reproducing the grey room itself, from the digital to the material world.

This notion of *the Grey Room* stuck with me, as it recalled my own, admittedly amateurish, experiments with Rhino and Grasshopper; the viewport of Rhino presenting a vast grey expanse with a grid at the centre to assist orientation. Grid or no grid, establishing a sense of scale in this

grey expanse remained tricky for me. So how do designers approach this grey expanse creatively, to make something meaningful out of its vast potentiality?

Resolution of complexity

When speaking to architects at the studio of 3XN and GXN, the story goes that where architecture excels is in the creative resolution of the complex dependencies of a brief into compelling, aesthetic and functional solutions. As we have seen, digital modelling is essential to this. Whether through finding form of designs, managing geometry, controlling data, or elaborating construction detailing, digital modelling allows designers to resolve complexity into coherent buildable designs. This marrying of form, function and aesthetics is a cornerstone in the creative practice of 3XN and GXN and finds its way into Kasper's quote, about how his interest in computational tools have moved beyond concerns with form to focus on potential new value-adding relationships these tools can impart to projects.

Modelling relationships between aesthetics and building tectonics has been a driving concern in architecture since its intellectual formalisation in the renaissance. Leon Battista Alberti not only formalised a modern notational system for architecture, setting design on its modern intellectual footing, but also produced models to work out his designs (Smith 2004:28). Gaudi used the physical pull of buckshot weights on interconnected hanging chain models to approximate optimal curves for the vaulting of his neo-Gothic architecture (Burry 2006, 2011b). Danish Architect Jørn Utzon (Mindrup 2019:203) famously proved the buildability of his 'spherical solution' for the Sydney Opera House by carving its characteristic shells out of a half sphere to show that their properties were rational, could be calculated and thereby prefabricated. In each of these examples, architects have married original aesthetic designs with complex structural calculations, resolving a complex problem through the use of material models.

Small and large-scale physical models have always played an important role in the realisation of architectural projects, providing architects with a sense of space, scale, and materiality of their design before it was actually built. These examples underscore my argument that we use material engagement to recast complex problems into more meaningful terms. Physical models allow architects to engage tactilely with geometry, structural elements, and fabrication concerns. They allow them to explore, understand and communicate an interplay of function and aesthetics which would otherwise be too complex to grasp (Yaneva 2009b:138). As we saw in Chapter 5, digital models at 3XN and GXN serve a similar purpose of managing complexity at a human meaningful scale. The digital modelling platform anchors a multitude of relationships between design practices and underlying software logics allowing architects to selectively blend additive, associative, and object oriented approaches to the creation and elaboration of geometry and construction details.

By combining geometry with mathematical precision, computational tools offer the possibility to introduce complex dependencies into the relationship between form and its representation, and to many commentators, computation has introduced a new focus on topology and mathematics in architecture (Agkathidis 2015, Lynch 1993, Schumacher 2008, Picon 2010, Burry and Burry 2010, Carpo 2011, Davis 2013a). The rise of parametric software in architecture has seen an intensification of information in digital models and the creation of forward-thinking structures, such as Zaha Hadid Architects' Lotus, which fully embrace this informational complexity. But as Lasse explained, the increasing reliance on parametric functions that do not have an inherent human measure can lead to a potentially disorientating lack of centre and scale as form and detail can multiply endlessly inwards and outwards in this digital design environment.

In winter 2017, I interviewed Jesper, 3XN Studio Director and an experienced project manager in the Competition department. He began our conversation by bringing up the difference between physical and digital models in design:

> I believe we experience form and volumes differently when seeing them in – let us say real 3D, than when seeing them on a screen. I find it interesting that perception of physical models and digital models is a bit different, so we try to create the things we find interesting in the digital world in parallel as physical models.

In this opening discussion Jesper emphasised that digital design and sketching was a prerequisite for work in 3XN's Competition department. This, he said, was why he was pre-occupied with the differences between digital and physical models; it was a question of precision, of understanding the implications of spaces, volumes and scale: 'You risk losing a sense of scale when viewing volumes and surfaces in a computer model, seeing the physical models gives another sense of proportions. You can assess the design language differently and perhaps more precisely.'

Lasse's notion of the Grey Room, captures the same challenges Jesper attests to as designers seek to work creatively with screen-based 3D modelers. The difference in perception of 3D models on screen and in the physical world is a core condition for practice at 3XN and GXN. Still, architects at the studio evidently master these differences, turning them towards novel answers to architecture's age old value proposition, the resolution of complexity into beautiful, functional and above all meaningful buildings and spaces.

6.2 Embodied mind in digital design

From Vitruvius' (2009) *Ten Books of Architecture* onwards, questions of scale and proportion in architecture invariably converge around the measure of the human body[19]. The classical ideal of architectonic embodiment correlates scale of building interiors with the proportions of an idealised human form (fig. 6.1).

[19] Today, the nature of this embodiment have been variously questioned and redeveloped under the influence of for example phenomenology (Bachelard 1957, Rasmussen 1956), and neuroscience (Sussman and Hollander 2014, Pallasmaa et al. 2013).

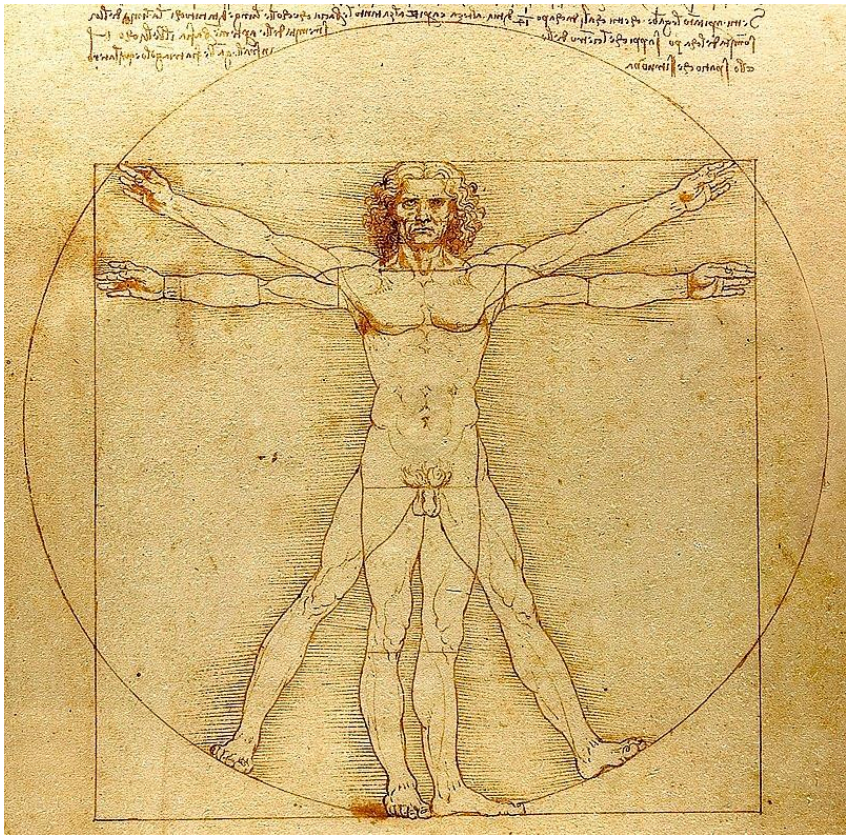

Fig 6.1. Leonardo da Vinci's *The proportions of the human body according to Vitruvius* (c. 1490).

This convergence of body and design reveals a deep involvement with how aesthetics connect to a human sense of scale, which survived throughout architecture's modern development as a discipline. It also came, for example, to inform the functionalism of Le Corbusier's (1961[1954]) Modulor, an anthropometric scale of proportions based on a man with his arm raised, which Le Corbusier used in the design of several buildings.

Both the original Vitruvian ideal and Corbusier's Modulor points to an important correlation between the experience and work of the designer: namely that the body is the designer's first tool, making embodiment the prerequisite for creating a sense of scale and meaning in design work.

As Lasse and Jesper attest to, the addition of progressively more advanced tools to this first instrument entails a practical remove from the inherent scale of the body as increasing complexity is imported from computer science and mathematics, and architects come face to face with the

bewildering expanse of the Grey Room. If this is the case, how do architects re-establish a sense of scale when working with digital design tools? Enactivist approaches to embodiment of mind and perception can help answer this question.

Embodiment of perception and mind

Enactivist approaches to embodiment of mind rests on the view that *perception is for action* (Gallagher 2017, Hutto and Myin 2013, Thompson 2007, O'Reagan and Nöe 2001, Varela, Thompson, Rosch 1991). Accordingly, perception is not something happening to us, but something we do, and as something we do it engages the whole body as well as the tools, materials, people and environments that we invariably interact with. This action-orientation entangles perception with embodied activity at all levels, from the muscle and eye movements guiding our use of tools, to the endocrine chemistry regulating our various responses, surprise, pleasure and distaste of the results. Perception and mind emerges from these myriad sensorimotor connections between active organisms and environments.

Just as the focus in Material Engagement Theory (Malafouris 2013) and cognitive ecology (Hutchins 2010) is on relations between ourselves and our environment, so the unit of analysis in the enactive view is not the brain in isolation, but the active entanglement of mind-body-environment. The sensorimotor account of perception developed by philosopher Alva Nöe and psychologist John Kevin O'Regan (O'Regan and Nöe 2001), draw attention to this world-involving aspect of perception, treating vision as: 'a mode of exploration of the world that is mediated by knowledge of (…) sensorimotor contingencies.' (ibid. 940)

O'Regan and Nöe define 'sensorimotor contingencies' as the structure of the rules governing sensory changes produced by various motor actions (ibid. 941). As we move around spaces, cast our eyes around on our surroundings, look at walls and furniture, take in the play of light on their

surfaces, and so on, our perception of these surroundings distort in lawful ways. These distortions are the sensorimotor contingencies doing the heavy lifting of perception for O'Regan and Nöe and they come in two instances: distortions produced by the eye and body, and distortions produced by the appearance of objects in space.

The first are distortions introduced by the eye and visual apparatus itself. As an example, O'Regan and Nöe point out that when our eyes rotate, the sensory stimulus on the retina shifts and distorts in a specific way, which is governed by the size of eye movements, the spherical shape of the retina, and the nature of the ocular optics. The second series of contingencies is related to the appearance of objects occupying 3-dimensional space. The retinal image of an object only provides a frontal view of the object, and this view changes as we move around the object and parts appear and disappear. Our distance to the object also governs the way it appears to us, becoming smaller as we move away from it and large if we move close. Movements will also distort the way light reflects from the object as we, the object or the light source move relative to each other.

Consider Jesper's interest in physical models in light of this. With a physical model, the designer can move around it, move the model, get closer to certain details, see how geometry and light affect each other as he moves, and so on relying on these sensorimotor contingencies to grasp aspects of the wider design through the scaled model. The sensorimotor contingencies of O'Regan and Nöe, distortions introduced by the visual apparatus and the appearance of objects in 3D space, help explain how the body becomes vital for enactive mind by showing how the richness of perception unfolds as minute possibilities for calibrating perception in action. Our habitual knowledge of these bodily and physical distortions allow us to deftly navigate through spaces with little thought to the enormous loads of information shaping the situation and the constant shifting of attentions and tensions between body and environment. With this in mind, Jesper's interest in the relationship

between physical and digital models take on extra meaning as it is not obvious how these sensory-motor contingencies fare in the relatively impoverished expanse of the Grey Room.

Sensorimotor contingencies and digital materiality in 3D modelling

In the preceding chapter, we saw that part of the efficacy of the digital modelling platform at 3XN and GXN was that it allowed architects to selectively blend and shift between different aspects of the larger model dependent on the problem at hand. These practices distribute material agency between architects and modelling platform, and rely on the affordances of different digital materiality of various software. Digital models allow architects to zoom in on and examine details at one moment and explore their global expression the next. But this forces designers to come to terms with a fluid multiplicity of scales and details in their work.

Consider, once again, Morten, a core member of GXN's Digital Design section working on construction detailing on the crystaline façade of the CUBE Berlin building. The façade is made up of 48 different planar surfaces, subdivided into 5.000 glass panels across 774 different shapes, that are precisely distributed at different angles to the building grid such that the overall kaleidoscopic façade effect is achieved. As we saw in Chapter 5, this combination of aesthetic vision and relative structural complexity is the result of ongoing modelling and adaptation of façade elements and construction details, which is anything but simple; changes to a parameter in the detailing, for example for how to attach façade panels to the building, will cascade through the parametric model with both local consequences (to the stresses carried by joints and fittings) as well impacts on the macro scale (the geometry of façade modules, the dynamism and tension of the façade). Resolving these tensions in modelling requires a fluid engagement across very minute structural detailing with tolerances down to centimetres and macro scales measured in tens of metres. How do architects keep the intricacies of these details and their global relations in their head at the same time? The

simple answer seems to be, they do not. This is the argument of material anchoring and functional simplification in cognitive ecologies, which I advanced in Chapter 5. Similarly, according to O'Regan and Nöe: 'It is just bad phenomenology to assert that we take ourselves to have a 3D-model or picture in the head when we see' (O'Regan and Nöe 2001:962). Bringing the two arguments together, I posit that perception and a sense of scale within 3D modelling environments resides not primarily in the brain of the architect, the complexity is simply too high, but rather in the enactive extension of mind enabled by ongoing manipulation of the digital model.

Sensorimotor contingencies in digital modelling

In all of my observations of architects' onscreen work in 3XN and GXN, the digital model being worked on was rarely left still for more than a few seconds at a time. In Chapter 4, Sean was demonstrating this continuous and lively action when creating his input to the Digital Factory workshop. He was clicking and moving the model in a creative flow where, rather like a potter at the wheel, his design developed through this close engagement with the digital materiality of his design environment. In their studies of architects working with software, sociologist Christian Heath and Paul Luff (2000:163) found a similar propensity to move, pan, zoom, and shift between layers of digital 2D floorplans. Heath and Luff link these movements to a architects maintaining a spatial awareness of the design and 'symmetry of the building' (see also Houdart and Minato 2008:158).

At 3XN and GXN, the digital model is constantly worked at, zoomed in and out of, moved around and rotated along its x, y, z axes. Trying to follow the many rotations, zooms and movements before it comes to rest on a detail can be disorienting for the onlooker not knowing what comes next, but I argue that the incessant movement serves an evident purpose for the architect; it helps ground her in the model's specific 3D spatiality. Rather than physically walking

around a model, the designer can spin it on the screen and view it from any angle or distance. Designers use their mouse to turn, scroll, drag and shape on-screen geometry, work out minute construction details, and move the viewport around to understand the 3-dimensionality of their creations. With Sean we saw how digital design alternated between periods of high activity with design functions, continuously dragging and changing geometry to see what happens, and shorter periods for contemplation, where continuous movement and rotation of the on-screen geometry helped build a deeper understanding of the 3D impact of a given operation.

O'Regan and Nöe (2001:942) relate perception in action to the movements of the grasping hand, linking sensorimotor contingencies to the tactile sense, as visual distortions in our perception of 3D objects can be apprehended by reaching out, grasping, and manipulating them. This link is key to bringing eyes and hand together in visual perception.

Perception in digital design and modelling similarly seems to rely on establishing and probing visual and sensorimotor contingencies between eye, hand, and screen. The hand movements of the designer working with mouse and keyboard, and the subsequent response of onscreen geometry, correlates the embodied sense of scale inherent in the designers movement to a sense of scale and three dimensionality in the design model. Anyone who has tried to fiddle with the sensitivity of their personal trackpad or mouse can testify to the surprising realisation that movements so tiny and routine as to become nearly invisible intimately connect the body to their computer. In this sense, digital design is quite literally perception in action, mediated by the architects' embodied familiarity with their digital tools.

As Lasse and Jesper both underline, the visual perception inherent in working with onscreen 3D geometry can feel less rich when compared to perception and movement in physical environments. Therefore, working with geometry on-screen requires constant manipulation of the model to maintain a richness of sensorimotor contingencies that allow the designers to establish and maintain

a sense of scale and proportion. Unlike the spatial world that surrounds us, the 3D world on screen is a flattened image projected as pixels on LCD screens. Establishing a sense of scale in this flattened environment is reliant on sensorimotor contingencies as highlighted by O'Regan and Nöe. But on closer inspection, the comparative 'flatness' of the Grey Room seems to impact the relative weight of these contingencies.

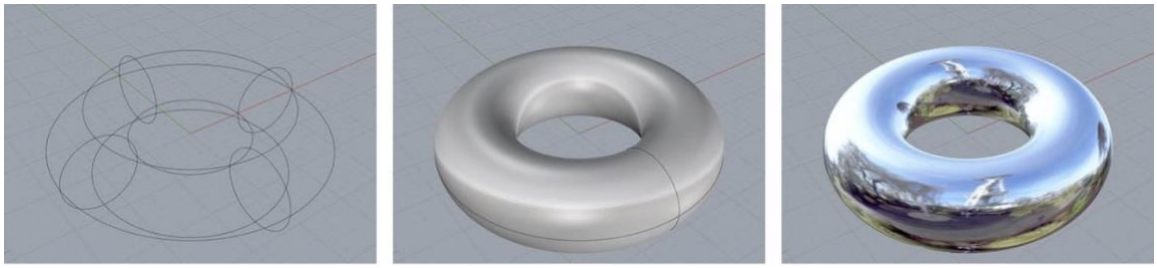

Fig. 6.2 'Wireframe', 'Shadow' and 'Render' 3D views of the same object in Rhino.

On screen, the contingencies introduced by the visual apparatus (distortions governed by the size of eye movements, the spherical shape of the retina, and the nature of the ocular optics), might not be enough to fully establish an understanding of the fluid three dimensionality of minute detailing at one moment and overall form and design expression the next. Rather this comes to rely on the contingencies introduced by a combination of design software and the computer's powerful graphics engine; such that the model's three dimensional shapes, its details and shading, the way light and glare is introduced in certain view types come to form lawful 3D distortions when the designer moves the 2D image on screen (fig. 6.3).

Digital materiality and enactive mind

I have defined digital materiality as the way successive layers of mathematics, code, and software come to mediate and shape architects' creative and collaborative work. It is my argument that if we want to understand the architect's digital modelling work, we have to understand how

mathematical, computational, and technical configurations of software come to shape patterns of interaction between architects and between architects and digital models.

Contemporary design modelers utilise the powerful graphics processing capabilities of computers to create a sense of fluid and dynamic manipulation of geometry on screens. In this, the coding of visual graphics of 3D modelers seeks to effectively re-create stable sensorimotor contingencies from our physical world and link these to the control of the designers' mouse to allow them more minute control of their model. In Rhino, for example, my observations of architects at 3XN and GXN saw them routinely toggle between different three dimensional views of models including wireframes, solids, and shaded objects, which enable different ways of exploring the models 3-dimensionality when moved around (fig. 6.3).

The feedback from the architect's input by hand and mouse to movements of the model is instantaneous and results in lawful distortions of these views on the screen[20]. This means that contemporary design software lends itself to explorative discovery not dissimilar to the creative process of pot-making put forward by Malafouris (Malafouris 2014). As argued in Chapter 4 on Sean's design research for the Digital Factory project, creative work of this type, requires constant reflexive movement of the model, which deforms and transforms for each of these movements through stable patterns encoded by the Rhino software's graphics kernel.

Building on this, my argument is that attunement to the contingencies of a specific digital model in the software environment is enacted through ongoing movement of the model and corresponding changes in its 3D appearance. This embodied perception in action is key for establishing and maintaining grip on the model's fluid multiplicity of scales, and for keeping its three dimensionality perceptible on the screen. This type of minute embodied interaction with the model helps establish

[20] The importance of this link between hand movement and instantaneous feedback in geometry on screen for enabling embodied perception in digital design was first suggested to me by Christian Mosbæk Johannesen at the University of Southern Denmark (private conversation).

and understand the situational spatiality required for 3D perception and design thinking in computational modelling.

Philosopher Eric Rietveld (Rietveld & Brouwers 2016, Kiverstein & Rietveld 2018, Bruineberg & Rietveld 2019) has explored how architects engage selectively with the multiple affordances available in design situations to advance possibilities for creative extension of mind. For Rietveld, mind is enactive and emerges in the interplay between rich landscapes of material, social and cultural affordances and the skill of the architect's response to these (Rietveld and Kiverstein 2014).

Rietveld and colleagues have advanced the notion of *skilled intentionality* to discuss how architects coordinate between several, sometimes competing, affordances in a given situation (Rietveld 2013, Bruineberg and Rieveld 2019, Rietveld and Brouwers 2016). They show how this works from within the architecture studio by discussing how designers simultaneously interact with software, sketches, and other people by directing attention towards salient aspects of these through intense creative engagement (Rietveld and Brouwers 2016). Skilled intentionality seeks *optimal grip* on the design situation, explains Rietveld, meaning a reduction in tension through interactions that seek to bring aspects of the competing affordances into alignment with specific goals such as evaluating sketches, discovering a better design, or advancing the situation of design itself (ibid.)

In the field of digital design we have seen embodied engagement with the affordances of 3D models, design software, computers and screens as an example of skilled intentionality seeking optimal grip. By constantly shifting perspective and scales, the architect seeks to ground herself in the digital design situation and reduce the tension inherent in the fluidity and relative visual poverty of the 3D modeler which was highlighted by Lasse and Jesper.

Rietveld explains that skilled intentionality reaches beyond the immediate goals of design to also reflexively encompass the situation of design itself (Rietveld and Brouwers 2016); the digital design situation is enacted with software and screens, a cognitive ecology that blends affordances of digital

materiality, embodied perception, and the personal experience of the architect. This advances the argument creative extension of mind, which I seek to develop here, by bringing attention to how discovery and learning are key for skilled intentionality, and therefore how the personal experience of architects come to vitally inform their ability to respond to certain affordances in digital design.

In presenting perceptual experience as an entanglement of designer with dynamic situations, the enactive view presents computational design thinking as inextricably entwined with bodies, tools, and environments. However, as we have heard from Lasse and Jesper, these entanglements require skill, and can remain difficult to navigate when compared to the physical world. Rietveld shows how this skill is part and parcel of the history and learning of architects, which shapes their possibilities for recognising and responding to the multiplicity of affordances available in a design situation. O'Reagan and Nöe forward a similar argument: 'Visual experience rests on know-how, the possession of skills.' (O'Regan and Nöe 2001:946), and these skills are grounded in the body[21]. From this, the question arises how do architects at 3XN and GXN build up this skill and familiarity with their computational tools in order to work creatively and intuitively with them?

6.3 Computational design thinking

The question of skill in digital design is tied to the history and experience of the individual designer. As Kasper and Lasse had explained to me when showing works from the 2008 Venice Architecture Biennale, their personal engagement with design tools had shifted along with new concerns and interests. For engaged digital designers, this personal relationship to tools extends further than critical appraisal of their results. During an interview in winter 2017, Laura, an

[21] Here is O'Reagan and Nöe (2001:944) on visual awareness: 'For a creature (or a machine for that matter) to possess visual awareness, what is required is that, in addition to exercising the mastery of the relevant sensorimotor contingencies, it must make use of this exercise for the purposes of thought and planning.'

experienced Competition and Project Development architect, explained that the models and scripts created using Grasshopper bore clear signs of their creator:

> Everyone has their own signature. Just like you have a different way of writing than I do and it reads differently. Some people can read your handwriting, and some people cannot read mine, in the same way it is pretty hard to read other people's scripts.

It seems the relationship with computational tools is very much a personal one. At a first glance it might seem counterintuitive that the rule based environment of computational design produce radically different scripting signatures from designer to designer, but I will argue – along with the architects at 3XN and GXN – that personalisation is a necessity stemming from the open-endedness of the digital design environments themselves.

Computational design thinking

Computational design thinking, working creatively and fluidly with digital design tools, requires personal investment. Architects Achim Menges and Sean Ahlquist describe computational design thinking like this:

> Fundamental to computational design is the understanding of how systems, as form and as mathematical ordering constructs, operate. Fundamental to understanding their operation is the level of prediction contained in the model which envisions the system. (Menges & Ahlquist 2011:16)

The position of the architect is changing, explains Menges and Ahlquist, as computation relies on the purposeful establishment and execution of rules for the development of forms, and not necessarily final forms themselves. This is why it is fundamental to understand 'the level of prediction contained in the model which envisions the system', and this understanding is established through ongoing design research where architects seek to explore the possibilities and limits of their computational tools. Think of Sean working out single block designs for the Digital

Factory project in Chapter 4 and his understanding of the limits of the design system which enabled him to know which designs would 'break' the setup and which were feasible.

The historic outline of digital design in Chapter 5 showed how computational tools have introduced a new array of parametric relationships into architectural practice, allowing geometry to translate into data and data to geometry. The combination of 3D design tools, like Rhino, and parametric programming environments, such as Grasshopper, introduce new practices along with the possibility to introduce complex causalities into the relationship between form and its representation. In winter 2017, I interviewed Dora, an experienced digital designer in 3XN's Competition department, she began by explaining her own preferences for working with specific tools from within this multiplicity of practices:

> Everybody works in different ways … I know that some are using hand modelling in Rhino, I personally prefer generative tools that I develop for a specific purpose, so, because it is based on parameters it can be changed easily.

Generative tools rely on parametric scripts to create and explore form, Dora explained. Scripts, whether a quick sketching of an idea or a complex analytical model, are personal for the designer who have made them, and Dora explained, become a personal vehicle for discovery and iteration in the context of design projects.

As Menges and Ahlquist point out, and as we have seen in Chapters 4 and 5, there are fundamental rules and constraints to computational design environments, but the modular and recursive nature of code means that these environments can carry out a seemingly endless array of operations, blends, and syntheses. If a form can be explicitly stated in parameters and mathematical relations between them, then it can be manipulated and operated upon in the scripting environment. Menges and Ahlquist (2011) offer a concise definition of the process of computational design thinking in the space opened up by digital tools, but in their definition it remains unclear exactly how creativity and collaboration play out in the rule-based but open-ended environments of

computational design. Dora points toward the answer in emphasising how she has found her own personal preference while highlighting that 'everybody works in different ways'.

Navigating the open-ended territory of parametric design tools becomes personal exactly because of the open-endedness introduced by the digital materiality of the tool. It becomes social as these tools link designers to their projects and teams (Ch. 8). Personal experience and engagement in collaborative contexts is necessary for mastery as well as for channelling creative work meaningfully into project work at 3XN and GXN. While I was a the studio, Kenn, one of the key architects in GXN's Digital Design section, would often discuss the high level of digital skill amongst many of the interns coming through 3XN and GXN, but would also lament the fact that knowledge of the radical opportunities of software could be difficult to translate into meaningful work on 3XN projects: 'It is all good and well that you know how to drive fast in the Ferrari, but if you do not know why…' he exclaimed one day we were discussing this, pointing to the importance of fitting personal preferences for working with tools within the social context of the studio. Understanding the 'why' in the context of 3XN and GXN, he explained, required an understanding of the needs and constraints of architectural project work that could only be borne from actual studio experience (see Ch. 8-9). This ability to bridge the technical and social complexities of digital design in the studio context is developed through ongoing design research.

Design research and digital skill

The computational space between form and representation introduces a radical open-endedness into digital design practice. Design research is fundamental to cultivate the experience that allows architects to engage skilfully with the myriad of affordances presented by their tools and the intensely social environment of the design studio. As Dora explained, developing an idea through a quick script or the construction of a complex generative model counts as design research as it can

reveal new insights about site, brief, form, structure, and related design problems[22]. It also reveals new insights about the tool themselves, and just as crucially as argued by Kenn, it situates these insights within the specific context of the 3XN and GXN studio. The move towards optimal grip on the digital design situation which has been highlighted by Rietveld and Brouwers (2016), is vitally dependent on design research as an enactive technique for bridging the technical and social aspects of digital materiality.

Design research in architecture has received increasing attention in the past decades (Frayling 1994, Archer 1995, Henschel & Nilsson 2015, Burry and Burry 2016). In an early and influential article on the nature of design research, former Rector of the Royal College of Art, Christopher Frayling (1994), highlights the many relationships between art, design and research practice. Frayling identifies three approaches to knowledge in art and design and three modes of questioning: research *into* art and design ('How can I tell what I think till I see what I say?'), research *through* art and design ('How can I tell what I think till I see what I make and do?'), and research *for* art and design ('How can I tell what I am till I see what I make and do?') (Frayling 1994:5). In the first category we can place theories of aesthetics, art and design as well as art and architectural histories; this line of research deals in declarative knowledge, it is descriptive and propositional. The second category encompasses various strains of what Herbert Simon (1996) has called *the sciences of the artificial* materials science, IT, genetics and other poietic disciplines; while knowledge for this type of research might well be declarative, it tends to be procedural, open-ended and generative as well. In the third category we find craft and art proper. Here comprehension is inextricably entangled with practice and artefacts; knowledge is deeply procedural, tacit and expressive and tends towards dealing with normative questions and answers.

[22] Design research is a constant throughout a project's lifetime. It goes on during form finding in early phases, through modelling and scripting as designs develop, in structural analysis during construction detailing, and at times through analysis and feedback during construction (see IOC project in Ch. 7-9). Within GXN design research also becomes the focus of in-depth research into materials, buildings, biology, and technologies (see Digital Factory project in Ch. 4).

Frayling's three categories are heuristic. It should be clear to anyone with even a passing interest in the sociology and philosophy of science that divisions between types of questions and knowledge will never be as clear-cut as the above framework suggests[23], but the modes of questioning *into*, *for*, and *through* art and design establishes a practical vocabulary for discussing the epistemological richness at play in design research and how this enables architects to familiarise themselves with their tools.

In our interview in winter 2017, Jesper explained to me how concept generation at 3XN's Competition department relies on an initial period of very open-ended digital sketching, where members of competition teams get to produce a vast number of ideas in order to understand the project. He explained: 'Different projects are driven by different concerns – what is often required is finding that one thing that sort of crystallises the project for you and allows you to get a hold of it and begin to construct an idea around.' Finding *that one thing* relies on the production and interplay of digital and hand drawn sketches, 3D geometry, physical models, scripts, images, textual analysis of briefs, intellectual ideas and cultural insights. In this, design research at 3XN's Competition department combines all the modes of enquiry forwarded by Frayling, mixing questions and knowledge, alternating between the propositional, procedural and normative, between science and craft, declarative and normative architectural statements.

As an example of design research in the Competition department, and in order to understand the ways in which design research contributes to an architect's learning and skill, consider the work of Sean, a skilled digital designer working at 3XN after his internship in GXN. When I interviewed Sean one evening after work in winter 2017 he was at the early stages of a two-month competition project. At this stage, he was concerned with form-finding for the project and the relatively open

[23] Frayling himself never ventures this far, but sticks to the more vague typology of the questions cited above, and mentions Paul Feyerabend, Harry Collins, and David Gooding to show how his contemporaries in philosophy, sociology and history challenge clear cut distinctions between disciplines and types of knowledge (Frayling 1994:3).

ideation process at the start of the competition gave him a chance to invest himself, his interests and ideas into this process. He explained:

> I have some ideas about what architecture should be and what would be suitable for this project. Ideas about taking inspiration from nature, from fluid mechanics, from quantum mechanics [laughs] some quite abstract things, but kind of trying to solidify it into a built project.

These ideas form the background from which creative impulses for how to apply computational tools to the specific project emerged: 'So for the last couple of days I have been doing a lot of scripting, particle simulations and vector fields and flows, trying to emulate fluid dynamics,' he went on. Examining the 3D movement of these flows as they meet the physical topology of the site of the building allowed Sean to explore potential geometries that responded directly to relationships which were not necessarily visible in the brief but could be teased out through simulation and scripting[24].

Importantly this process of form finding does not rely on blindly running scripts but is directed and continuously evaluated, not necessarily for a final form itself, but for new insights about how form can relate to the site. Sean elaborated:

> I make it, knowing that it is not going to be anywhere near as crazy as that. It is part of an exploration of ideas and what you can learn from that, and then you can implement some of the lessons you have learned from that into the final, more rationalised design.

This brief example shows how design research on projects at 3XN's Competition department mixes types of enquiry highlighted by Frayling. Sean's explorations engage with propositional knowledge from science and physics, poietic scripting into relationships between site, forces, and geometry, as well as normative evaluation and judgement by Sean and later the wider design team.

[24] Computational Fluid Dynamics is a powerful tool using numerical analysis to simulate problems that involve fluid flows. In architectural design these flows can include amongst other things wind, rain water, or people through spaces which are used to improve building design by e.g. minimising wind tunnel effects, ensuring efficient rainwater runoff or securing efficient and safe movement through busy spaces.

This combination establishes a rich background for inspiration and ideas. It also invariably allows Sean to learn new lessons about the computational design tools he is using, including plugins and custom tools for simulating flows and fluid dynamics in the Rhino/Grasshopper environment. And importantly, considering Kenn's comment on the 'why' of digital scripting, it does so within the context of a 3XN competition project. The results of this labour are shareable and indeed must be shared in the competition team to have any effect, but they are also deeply personal and tied to the interests and specific skills honed by Sean as well as his normative ideas about 'what architecture should be'. In this way, Sean builds up familiarity with quite advanced computational tools within the context of the 3XN and GXN studio, which enable him to apply these skilfully and creatively.

6.4 Design research and embodiment of mind

Computational design thinking and research entails a personal mastery of multiple modes of enquiry as they pertain to form, software, and mathematics. During our interview Laura explained: 'Grasshopper is of course very graphical but there is so much math behind it. I think the reason why there is such an enormous difference [between digital designers], relates to the way people internalise mathematics and geometry.'

Ways of reasoning in these open-ended scripting environments become intimately linked to the experience of the individual architect exactly because of its open-endedness. The ability to bring forth and grasp creative ideas is established through design research, allowing architects to understand relevant affordances and digital materiality of their tools by experimenting with them in context of actual design projects. Laura elaborated:

> I think it comes from the way you string things together. If I asked you to figure out how to solve some task, there would be many different ways to do that and maybe we would not pick the same … Somehow your brain shortcuts in different ways, and I think that is a big part of the way people script in any language.

The moment of inspiration, recognising and responding to the affordances of digital design environments, what Laura calls ‘the brains way of shortcutting’, is crucial in working creatively with digital models and scripts in architecture. And this moment is enacted against a background of embodied engagement, learning, and enquiry, core elements in the history of anthropology.

Design research as technique of body and self

While embodiment has not been at forefront of anthropology until recently (see Desjarlais and Throop 2011, Lock 1993), it has nevertheless been present from the early days of the discipline. In a seminal paper on techniques of the body, presented in 1934 at the Société Française de Psychologie, Marcel Mauss’ (1973[1935]) discussed how we come to do things the way we do.

Mauss paid special attention to the way the body mediates between social, psychological, and biological aspects of life. He began his lecture by inviting his listeners to consider an experience from his own life: falling ill and going to the hospital in New York. Here, Mauss spent some days fascinated by the bearing and walk of his American nurses. He realised that the young nurses tending to him were mimicking the gait of the starlets and femme fatales of the movies coming out of Hollywood. Mauss used this to explain how the new mass medium of film had captured the imagination of society to the point of changing intimate cultural mores (upon returning to France, he further noticed how widespread this same way of walking was becoming among the young Parisian women seeing the same films).

This example is instructive in several ways. It shows how even the most ‘natural ways’ such as walking unfold in a complex interplay between body, environment, and culture. It shows how these ‘ways’ are intimately linked to technology in both obvious and not so obvious ways, and that techniques of the body are refracted through the institutions, media and spaces an individual

engages with. Mauss certainly appreciated the example offered to him by his American nurses: 'This was an idea I could generalise,' he exclaims of his hospital visit. Looking at a wealth of bodily techniques, he arrived at the following generalisations: 1) there are no 'natural ways' of doing things, instead there are techniques of the body; 2) all techniques of the body are 'effective and traditional', that is, they are perceived as means to an end, are socially transmitted, and their influences on body and psyche are profoundly connected (Mauss 1973[1935]:75, see also Mauss 1984[1938]). In essence, Mauss arrived at much the same conclusion as Vitruvius, that the body was man's first instrument, and elaborated that the use of this instrument in everyday life is a craft that is learned in deep engagement with environments and others.

Mauss was adamant that the basic formula – *effective* and *traditional* – applied to complex and creative techniques involved in e.g. hunting and magic just as well as to the minutiae of everyday life. Just as there are techniques of walking, there are techniques of modelling, of scripting, sketching, and designing. Even though these are complex tasks, they share the same bodily and habitual grounding as we saw above in the section on sensory-motor contingencies.

Techniques of the body become manifolds for investigating the dynamic interplay between individuals and society by attenuating how biological, social, and historical practices flow together in embodied action. We have seen that bodily engagement with digital models is crucial for introducing a sense of scale into the digital design environment at 3XN and GXN; the many interactions between hand, mouse, screen, and eye amount to a technique of the body in the sense forwarded by Mauss, in that it is not 'natural' but learned. Developing this technique allows designers to ground themselves in their digital design environments. These techniques of the body effectively deal with the relative poverty of the digital space, which Lasse pointed to with his notion of the Grey Room, and Jesper highlighted in his comparison between physical and digital models.

In addition to mastering these techniques, Kenn highlighted the need for young architects to develop digital mastery in a studio and project context as well. There are clearly social aspects to these techniques of the body and self (see section on dividuality and digital materiality in Ch. 8). From Sean, Dora, and Laura we have heard that the interaction with different modes of enquiry and ongoing learning through situated design research is crucial for working creatively with digital design tools, and that this brings the personal development of the individual designer into play with the wider situation of the teams, projects, and departments in the studio. This interplay between individual and context is key to creative practice in computational design thinking and design research; by showing how it is mediated by the body we can begin to see the role played by embodiment and extended mind in complex cognitive tasks.

Plans and situated action in design research

Lucy Suchman's (1987, 2006) seminal work in Human-Computer Interaction (HCI) can extend the insights of Mauss with a framework for understanding how bodily engagement with digital tools integrate different modes of enquiry. In the 1980s, Suchman and her team at the Xerox Palo Alto Research Center focused their attention on how interactions between humans and (photocopying) machines were materially configured and enacted.

Suchman's work focused on the asymmetry in relative access users and machines had to unfolding interactional situations, namely that people had very few opportunities for understanding and changing how the machines worked while using them. This is comparatively different in digital design research, where architects have access to the underlying parametric relationships of their models, but Suchman's insights remain valuable for understanding how design research proceeds as an embodied activity integrating several modes of enquiry at once.

Suchman was concerned with what she calls the real-time contingency of situated action. She advanced an ecological approach to HCI where the key point of analysis was the interplay between *plans* and *situated action*. Plans, in Suchman's work, represent the explicit and imaginative formulation of a sequence of actions (at its most fixed, the steps required to operate a 1980s photocopier), while situated action represents practical on-the-fly reasoning (whatever we do once plans break down or stop being effective, which apparently was most of the time when it comes to 1980s photocopiers). Suchman does not simply criticise plans, as has been claimed by some of her readers (Suchman 2006:17), but rather interrogates the complex interdependency of both plans and situated action in giving rise to creative engagement with technology. Her work shows how plans are constantly reconfigured and adapted to the contingencies of actual interaction with technics. For Suchman, this constant back and forth: 'emphasize both the utility of projecting future actions and the reliance of those projections on a further horizon of activity that they do not exhaustively specify.' (Suchman 2006:19).

We have already seen how in digital design research, questions and plans do not exist in a vacuum but take on meaning (are enacted and reconfigured) through situated action in the context of actual design projects. Questions and plans ('an understanding of the level of prediction inherent in the model' as it were (Menges and Ahlquist 2011:16)) are integral to creativity and imagination in the studio of 3XN and GXN, but do not dominate creative ideation; rather they form dynamic repertoires of possible actions to draw on in unfolding situations, and the body is what mediates synthesis of plans and situated action within these.

Digital architects like Laura, Dora, Kenn, and Sean might start out scripting with a plan, or as Sean formulated it: 'ideas about what would be suitable for the project,' but once these ideas are encoded into generative scripts or formalised in models, they undergo change and reveal new

insight about the idea, about the project, brief or the site. In our interview Sean explained how he had used computational fluid dynamics to explore the project context:

> I was imagining on this project that you just have a solid volume, a primitive volume, like a cube or a sphere, or a cylinder. And you can imagine wind erosion, or water erosion just starting to chip away at this form, and you start to get this really organic looking thing. It is not the most elegant, and it is by far the least buildable thing we can do, but it was a start and there are things I can learn from it, and I can start projecting my own ideas about what should be here.

In this explorative process, knowledge of the tools (plans), only comes to take on meaning as a cognitive resource for design through ongoing exploration (situated action) in the context of the design studio. As Sean and Laura explained, digital design research becomes vital for the individual designer, not necessarily for producing specific results, but for deepening the experiential field from which creative and meaningful material engagement with digital tools can emerge and evolve. The flow of personal experience gives plans and situated action their meaning and efficacy through ongoing design research (see also Rietveld and Brouwers 2016, Bruineberg and Rietveld 2019).

Mauss and Suchman each point to the fact that our creative lives – thinking, doing and making in the widest sense – unfolds with and under the pressure of biological, social, and technical forces coming together to afford and constrain practical and cognitive opportunities available to us. Taking up a similar situated perspective, Hutchins (2010) introduced the notion of cognitive ecology to explain the dynamic interaction and mutual co-constitution of bodies, tools and culture. Malafouris (2013, 2015) introduced the framework of material engagement theory to explain the cognitive entwining of mind and materials across temporal timescales. Rietveld (Rietveld and Brouwers 2016, Bruineberg and Rietveld 2019) have introduced the notions of skilled intentionality and optimal grip to explain how the personal learning of the architect helps them respond selectively to the many affordances available in a design situation. Bringing these perspectives together, we can begin to see that cognitive ecologies in the studio of 3XN and GXN contain both past tools and practices (see Ch. 5), as well as past and present engagements and experiences of the architects.

These timescales – from the historical to the personal – flow together and become stabilised through situated actions, which give rise to skilled intentionality within material and social institutions. This deep engagement with shifting historical, material, social and informational elements gives rise to original insights and imaginative ideas (see also Ch. 4, Gallagher 2014:116). As Laura, Sean, and Dora explained, creativity arises from the many possibilities for combinations within this field; and sense-making through embodied practice becomes a key activity for exploring the affordances of new combinations. I have shown here that this is in no simple way contingent on the tool itself, but as much on the embodied experience of working with tool as this is refracted through personal experience and shared institutions.

Even for highly abstract mathematical entities, such as digital design models and computational fluid dynamics, a wide variety of bodily and conceptual registers and anchors are recruited to allow for their purposeful manipulation in the realm of aesthetic experience. As Dora explained, 'everybody works in different ways'. She continued: 'I think that is the fascinating part of it, not having a rule, so you actually just try to dig in, try to explore, and then pour the things in your brain out in a white canvas.' With the right form of training, experience, and skill, the Grey Room becomes a realm of possibilities rather than a disorienting interface imposing its inherent lack of scale and context on the designer.

Conclusion to chapter

Examining two aspects of computational design – embodied perception and design research – I have argued that modelling practices in the studio of 3XN and GXN relies on embodied engagement with digital tools. Their grounding for each designer relies on a personal history of

situated skilled engagement in the here and now but reaches beyond this to encompass the historic experience of working across a number of design situations.

Menges and Ahlquist (2011:16) point to an 'understanding of how systems, as form and as mathematical ordering constructs, operate' as the crux of this process. I argue that this understanding exceeds mental or static representations and develops through embodied engagement with digital tools in the context of studio projects, which advances the architects' understanding of the digital materiality of software environments and enables them to get a better grip on the digital design situation. In this way computational-design thinking proceeds not only through rule-based exploration, but also through creative, sense-saturated activity that reveal new opportunities in the dynamic systems that designers bring together through material engagement and skilled intentionality. In the field of Human-Computer Interaction, Suchman (2006) showed a similar reliance on embodied activity in the interplay between plans and situated action at the computer interface. I have shown that this integrative embodied perspective is working at several levels, including: the body as a measure of scale; the body as a loci of tacit skill and memory; the body as a medium for bringing disparate forms of knowing together in situated action.

The power of digital tools lies not only in the way their memory, speed and precision allow architects at the studio to control complex and dynamic systems, but also in their ability to combine a vast array of information at the scale of human perception and experience. Digital design research requires some understanding of all of these realms. Embodied material engagement is where these come together to create meaningful connections through the ongoing sense-making between designer, team, project, studio, tools and materials. Through this structural coupling, the experience of embodied practice comes to shape the creative extension of mind through digital design research.

Section III – Collaboration

> *The art of reasoning consists in getting hold of the subject at the right end, of seizing the few general ideas that illuminate the whole, and of persistently organizing all subsidiary facts around them. Nobody can be a good reasoner unless by constant practice he has realized the importance of getting hold of the big ideas and hanging onto them like grim death. (Whitehead 1913:92, quoted in Lawson 1994:139)*

This way, the philosopher Alfred North Whitehead defines the slippery relation between ideas and their context. Whitehead highlights thinking as a process, something we do rather than something that happens to us. In the literature on design thinking this process focus seems to have special resonance and Whitehead is cited several times. In *Design in Mind*, Bryan Lawson (1994:140) quotes Whitehead to explain how architects develop and sustain parallel lines of thought by hanging on to several unresolved ideas simultaneously during design projects. This enables skilled design teams, argues Lawson, to mix different expertise and ways of knowing throughout the process of design to arrive at better answers; an ability the digital modelling environment at 3XN and GXN support in new ways as we saw in Chapter 5. Introducing the essays in *Designerly Ways of Knowing*, Nigel Cross (2006:2) cites Whitehead to explain how designers bring together expertise from across art and science in a third domain, the domain of design thinking, which simultaneously creates and evaluates objects against normative demands in briefs. We found in Chapter 6 that this integration of formal and normative concerns was key to digital design research at the studio.

Lawson and Cross are influential thinkers in the field of design studies (see Dorst 2011 for an overview). Their focus on parallel lines of thought and mixing of expertise springs from the nature of the problems architects face in their projects. At 3XN, moving a project from early design concept to finished building requires the merging of ideas and skills from across design, architecture, and engineering. This entails close collaboration within the studio. While it has been hinted at in Section II, this section of the thesis will show how collaboration during all phases of

architecture projects requires persistent work to align embodied creative practices, digital materiality of design software, and institutionalised patterns of collective behaviour in the studio.

The work required to create and maintain alignment between people, ideas and materials have been a well-spring of creative thought in anthropology (e.g. Douglas 1966, Gell 1998, Ingold 2013). Mary Douglas explored the relationships between social life, knowledge, and material culture, and dealt imaginatively with the slippery relations between ideas and their contexts (1966, 1973, 1986). In *The World of Goods*, Douglas proclaimed: 'The main problem of social life is to pin down meanings so that they stay still for a little time.' (Douglas and Isherwood 1996[1979]:43) This notion of *pinning down meanings* seems to me to be a collective version of Whitehead's getting hold of the big ideas around which other facts can be organised. For Douglas this collective process is the foundation of society (Douglas 1986). Her work encourages us to think about how people come together to create relative stability out of the inchoate flux of events that surround them – and how this stability is constantly and creatively contested, manipulated, and re-imagined in social practice and, I will argue, social extension of mind.

Case study

Teams at 3XN and GXN must balance aesthetic, functional, social, technical, and economic concerns while developing architecture projects. In the three chapters in this section, I will explore these relationships by focusing on two such projects. The first, in Chapter 7 describes the creation of a design brief for a circular economy pavilion developed by GXN and a group of expert collaborators. The second, in Chapters 8 and 9, discusses competition design and project development of the 3XN designed Headquarters for the International Olympic Committee (IOC). These examples show how the integration of different ways of thinking into meaningful collective practice is mediated through digital tools and models.

At once open-ended and highly regulated, architecture projects like these provide an interesting venue for exploring overlaps between digital materiality and social mind in the studio of 3XN and GXN. The projects show how collaboration in the studio rests on the integration of different expertise and practices throughout a project's lifetime: open-ended ideation when developing design briefs and competition concepts; systematic problem solving during project development; and collective design research with expert collaborators to resolve more complex problems. As explored in Section II, this design work is embedded within shifting digital materialities that come to anchor cognitive ecologies (Hutchins 2010) at the studio. These allow designers to collaborate on solutions to the many problems that emerge throughout a project's lifetime. Analysing patterns of collective behaviour and organisation between designers in the studio will allow for further analysis of the social and technical interdependencies in these cognitive ecologies.

Chapters 7-9

I will explore and discuss collaborative practices at 3XN Architects and GXN Innovation across the different scales of *teams* (Chapter 7), *projects* (Chapter 8) and *studio* (Chapter 9).

Chapter 7 focuses on patterns of interaction within design teams, to show how these patterns provide the opportunity for participatory sense-making, and the merging of different forms of expertise and knowledge. I argue that institutionalised patterns of interaction become constitutive of social mind in design teams, and that the creative potential of these practices is dependent on accepted patterns of collective behaviour, which provide a meaningful context for social mind.

Chapter 8 expands the temporal scale of analysis by looking at the development of the IOC project from early competition phases to buildable designs. I discuss how architectural concepts are

shared in and between teams during a project's lifetime. This discussion utilises the anthropological concept of dividual personhood to explain how the exchange of digital scripts and models between architects come to facilitate participatory sense-making in architecture projects.

Chapter 9 describes the wider studio context of the practices first discussed in Chapter 8. I expand the temporal scale further by investigating how meaningful interactions are stabilised in institutionalised patterns of collective behaviour in the 3XN and GXN studio. This argument engages a dynamic version of cultural theory, inspired by Mary Douglas and further developed by Steve Rayner and colleagues, to show how different ways of organising collective behaviour shape people's possibilities for thought and action.

As Douglas makes us aware, stable meanings are only achieved through collective work. Architectural projects fit right into this category of socially produced stable meaning, after all they are stable enough to structure the years of collective work that goes into designing and constructing a building. In this sense, and paraphrasing her famous dictate, architecture 'is good for thinking with' (Douglas and Isherwood 1996[1979]:41). For the purposes here, architecture is good for thinking about that which is being created – concepts, models, scripts, buildings – as well as the practices of creation themselves. These practices are at once social and technical. They highlight the intimate relationship between the practice of architectural design and processes unfolding in the objects and contexts of design; its code (Ch. 4), its models (Ch. 5), its practices (Ch. 6), teams (Ch. 7), and projects (Ch. 8), as well as the wider context of the design studio (Ch. 9).

Chapter 7: Team

Drawing on the work of Mary Douglas (1986, Douglas and Isherwood 1996[1979]:43), I argue that a key problem for teams in the 3XN and GXN studio is creation of shared meaning in the form of architectural concepts that can serve as collective frames of reference for collaboration. Architects must work together to develop design concepts that can illuminate the whole of a project, and around which years of subsequent work can be organised. Design teams in the studio collaborate to pin down meaning in concepts that are stable enough to transmit shared meaning over the lifetime of a project, yet flexible enough to permit change as different forms of expertise come to inform this work. They anchor these concepts in digital models to work out the problems arising while developing projects into finished buildings.

Here, I will focus on the early stages of this conceptual teamwork and relate this to the specific nature of problems faced by architects. These are so-called 'wicked problems' (Rittel and Webber 1972). They are opened-ended and their answers are predicated on collective work. Understanding how this work relates to digital materiality and social mind requires analysis of what cognitive scientists Ezequiel Di Paolo and Hanne De Jaegher (2007) call processes of *participatory sense-making* (more on this below). I will focus on a GXN research project, I helped develop during my time at the studio. This project is somewhat different from most 3XN projects as it focused on defining a design brief before it was handed over to the design team. But I will argue that the collective sensemaking it entails is routine activity in the highly socialised world of the design studio. The case involved a group of partners who a had not meet before and therefore followed a fairly formulaic structuring of collaborative processes. This makes it easier to see how different institutionalised interactional dynamics come to enable social extension of mind by supporting different ways of probing the collective meaning of a wicked problem. But as we will see below, wicked problems are a routine feature of design. So is collective sense-making. This argument

follows Rieveld and Brouwers (2016), De Jaegher and Di Paolo (2007), Gallagher (2013), and Douglas (1986), as well as my field experience. Sean did not work out single block designs on his own but in close engagement with Morten and others in Chapter 4 (p. 116). From my own later experience working with GXN input to 3XN Competition teams, I know how difficult it can be to work creatively with a project if one is not quite literally in the midst its social development (see p. 228, 267-268). Here I will turn to why that is – and to concepts of social extension of mind.

7.1 Wicked problems and collective creation of meaning

At GXN a large part of my job consisted in helping develop research and design projects. Each project I worked on had different goals, different partners, and different barriers and opportunities; defining these opportunities always required cross-disciplinary collaboration in the project's team.

To understand the nature of this work, whether in GXN or 3XN, we must understand that it emerges in answer to specific needs. Design problems are open-ended (Lawson 1994:2, Cross 2006:7, Dorst 2011:522), and as new approaches and technologies come into architecture, architects face growing levels of complexity. Finding a strong concept for a project to cut through this complexity is in large part the first problem for a design team (see Ch 8 and 9).

At 3XN and GXN, finding these concepts are a collective task. I have not worked on any project, which did not require the merging of ideas and expertise from an array of disciplines. This follows a general trend in architecture, as argued in a recent special issue of the journal *Architectural Design*: 'Once upon a time, we might have seen architects as the conductor of the orchestra; now they are but one cog in a vast and increasingly complex machine.' (Hopkins 2018:11) In this section of the thesis, I will explore how this collaboration is configured and experienced at the intersection of technical and social mores. For the architects at 3XN and GXN, working creatively within this

‘complex machine’ is closely tied to different formats for collective thinking within teams whose collaboration is enabled by a constant production of meetings, sketches, scripts, and digital models.

Wicked problems in the architecture studio

Creative direction for a project is made through strong design concepts within research and competition teams at 3XN and GXN. These concepts enable 3XN Competition and Project Development teams to align aesthetics, function, and storytelling in their architectural solutions, and they get GXN collaborators excited about research projects. In both cases, teams face open-ended problems whose solutions are dependent on their context, but where neither context nor solution can be adequately grasped before trying to solve them.

In their seminal definition of ‘wicked problems’, design theorists Horst Rittel and Melvin Webber (1973) outlined ten criteria that set these types of problems apart. The criteria (fig. 7.1) emphasised that wicked problems have no definitive problem formulation, that there are no clear parameters for defining success and no rule to determine when a solution might be complete and hence when to call it a day and stop working.

1. There is no definitive formulation of a wicked problem.
2. Wicked problems have no stopping rule.
3. Solutions to wicked problems are not true-or-false, but better or worse.
4. There is no immediate and no ultimate test of a solution to a wicked problem.
5. Every solution to a wicked problem is a "one-shot operation"; because there is no opportunity to learn by trial and error, every attempt counts significantly.
6. Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan.
7. Every wicked problem is essentially unique.
8. Every wicked problem can be considered to be a symptom of another problem.
9. The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution.
10. The social planner has no right to be wrong (i.e., planners are liable for the consequences of the actions they generate).

Fig. 7.1 Ten Criteria of Wicked Problems (Rittel and Webber 1973)

Design theorists agree that architecture poses wicked problems of the kind where the information needed to understand them is dependent on the normative ideas advanced for solving them (Dorst 2011:522, Cross 2006:7, Rowe 1982:18) Since different formulations suggest different solutions, answers must necessarily be normative and partial, based on qualified judgement of design teams[25].

Social scientists will recognise that wicked problems are collective problems and therefore dependent on shifting social contexts for their definition and solutions (see Rayner 2006). It is impossible to separate fact from values in the formulation of wicked problems, which can lead to suppression of what anthropologist Steve Rayner (2012) has called 'uncomfortable knowledge,' and marginalisation of those whose point of view does not fit with the concepts advanced in problem formulations and solutions. Rayner defines uncomfortable knowledge as disruptive information which may be available to certain parties but cannot be acknowledged by others as it contradicts the versions of the world, they have pinned their professional or personal hopes to. Suppression of uncomfortable knowledge is concerning because wicked problems are entangled in series of other problems. Unintended consequences can scale quickly. On large architecture projects, where budgets, buildings, and reputations are at stake this can quickly become costly. There are no right answers, just better or worse solutions to wicked problems, and the only approach is to get your hands dirty.

As Rayner (2012, 2006) has pointed out, wicked problems encompass social institutions, economic concerns, and technical issues, and so does the knowledge needed for solving them. Architect and design theorist Peter Rowe (1991[1987]) has made a useful distinction between 'domain knowledge', encompassing how much someone knows about a particular field (e.g. Architecture), and 'structural knowledge', which involves how concepts of a domain are related

[25] This definition begs the question if this is particularly unique to wicked problems, or simply a fact of any problem that require socially coordinated effort to deal with as these will necessarily contain elements of uncertainty, blind spots and uncomfortable knowledge (Rayner 2012), leading to normative interpretations and potential disagreements.

(and can be manipulated). Domain knowledge can be explicitly stated and explained, structural knowledge less so as it is more tacit and based on the experience of the designer.

In Chapter 4, we saw how digital design research enabled domain knowledge about the field of robotic fabrication in the form of knowledge about robots, mathematics, and design workflow, and structural knowledge in the form of a tacit understanding of how these elements come together to make some designs possible and others impossible. Chapter 6 expanded this discussion by showing how design research helps architects build both domain and structural knowledge in the field of digital design. I argued that this enables skilled intentionality in the form of selective attention to aspects of the digital design situation which bring competing affordances into alignment with goals such as evaluating ideas, discovering a better design, or advancing the situation of design itself (Rietveld and Brouwers 2016).

From these examples it should be clear that domain and structural knowledge is intimately connected, and that their integration in architecture projects comes to shape the situations of design by introducing both explicit and tacit knowledge into the mix (see also Rowe 1991[1987]:112). For Rowe, the open-ended nature of wicked problems means that designers must mobilise vastly more knowledge than can be stated in a brief in order to arrive at satisfying answers. Therefore, the structural knowledge of architects becomes vital for dealing with wicked problems. Know-how about relationships between e.g. the digital materiality and affordances of software environments and institutionalised patterns of collaboration at the studio can only be amassed through years of hands-on work but is required to work efficiently as an architect (p. 116, see also Kreiner 2002).

This poses a problem for design teams. Social science and design theory (e.g. Rayner 2012, Suchman 2011, Lave and Wenger 1996, Kreiner 2002) argue that what Rowe calls structural knowledge can be difficult to formulate clearly as much of it exists as personal intuition and tacit knowledge. Michael Polanyi (2009[1966]:4) defined tacit knowledge as the skills and experience

people have, which cannot be easily expressed, in short: 'we can know more than we can tell.' Recalling philosopher Gilbert Ryle's (1949) distinction between 'knowing what' and 'knowing how,' Polanyi further stated that explicit knowledge and tacit knowledge is never present without the other (ibid. 7). An insight we also found in ethnographic examples of design research and in Rowe's argument about the dependencies between domain and structural knowledge.

I will argue that sharing of tacit structural knowledge can happen through collective creation of meaning of the type Douglas (1986) highlights as central to social life. Tacit knowledge is developed and shared in communities of practice in the architecture studio (Lave and Wenger 1991). This happens as aspects of both domain and structural knowledge are combined in design concepts that are stable enough to structure collaboration in teams with different domains of expertise. As examples and interviews in Section II showed, architects at 3XN and GXN rarely work alone for extended periods of time. Instead, they collaborate around the making and circulation of sketches, digital models, scripts and artefacts that are essential for successful teamwork. And successful teamwork is part and parcel of architectural design, as architect and researcher Enlai told me one spring day in 2018 when we were talking about his role as a design lead in GXN:

> The point about architecture and design is always that you are creating what does not exist (…) one of the most important things is to be able to tell yourself what you do and do not know, and to tell yourself what does and does not work. And in order to do that, communality if you like, or group work, or group behaviour, is very good, very useful. I think this is a desire that most designers have; *to work in that communal mind space*. Explaining yourself to others, testing reactions and asking for criticism are things you can't do without in design. (My emphasis)

Enlai talked about his work as a design lead for the *Circularity Lab* project, which I will analyse here to discuss what this *communal mind space* consists of.

The general point is that design work at 3XN and GXN is inseparable from the teams where it happens. These teams seek to mobilise several types of knowledge, both domain knowledge from

architecture and related fields, as well as structural and tacit knowledge from individual architects, to solve the wicked problems posed by design briefs and research projects. At 3XN's Competition department, Jesper, the Studio Director and an experienced project lead with many competitions behind him, described it like this: 'Different projects are driven by different concerns – what is often required, is finding that one thing that sort of crystallises the project for you and allow you to get a hold of it and begin to construct an idea around it.'

By talking about the necessity of getting hold of that one thing which can illuminate the whole and help crystallise a project, Jesper is essentially paraphrasing Whitehead's quote on the art of reasoning, which opened this Section. In dealing with wicked problems through design, teams at 3XN and GXN seem to have realised the importance of seizing on the key ideas that can be used to structure subsequent facts around. Of finding collaborative ways of pinning down social meaning.

Here, I will follow Douglas' notion that commodities are good for thinking with (Douglas and Isherwood 1996[1979]:41), but will be focusing on digital models, materials, and design objects rather than commodities. I will examine how the creation of meaning in both the objects and the contexts of design come to rely on collective action in teams, which seek to align people, technics, and institutions. This will further develop the understanding of digital modelling practice in the studio of 3XN and GXN, by adding situated social interactions to the analysis of digital materiality in material agency (Ch. 4), cognitive ecology (Ch. 5), and digital design research (Ch. 6).

7.2. Developing a design brief for a circular pavilion

Digital materiality seeks to analyse the way successive layers of mathematics, code, and digital interfaces come to mediate architects' creative work with computers and the possibilities of collaboration afforded them by software, scripts and models. Analysis of collaborative design

practices can help us understand how organisational and technical correspondences enable collective creation of meaning in teams at 3XN and GXN. Here, I focus on a GXN research and design project I helped develop during my time at the studio.

Contested concepts and collaboration

The research and design project was called the *Circularity Lab*. It brought together a team of interdisciplinary collaborators, including Arup, Turner Construction, and 3XN and GXN working together with support from Google to advance circular economy in the built environment. The goal of the project was to create a brief and design for a circular demonstrator pavilion to be built in New York to showcase circular construction principles. GXN were design leads for the project.

GXN had been working with *circular economy* in the built environment for close to seven years when the Circularity Lab project was starting up. Before the project, I interviewed Casper, a GXN project lead with much experience in this line of work. Circular economy is resource economy, he explained. The circular economy posits itself against the linear economic model of take, make, and dispose, seeking instead to create efficient material loops for circulating products and materials at high value for longer[26]. The end-goal, Casper explained, is to design away waste and reduce our reliance on finite resources. The concept promotes sustainable use of resources by designing products (e.g. concrete elements, façade shingles, carpet tiles) from high quality materials in ways that allow for them to be taken apart and reused again. This requires a holistic approach to design that considers the entire life cycle of a product as well as its stakeholders, economy, and environmental factors in its production and disposal. In construction, which is characterised by

[26] Circular economy strategies receive increasing academic attention (Ghisellini et al. 2016, Korhonen et al. 2018, Kalmykova et al. 2018), but have primarily been developed by non-governmental organisations (EMF 2015, EMF et al 2015, WEF 2018), and companies with a stake in the transition (Arup 2016, Jensen and Sommer 2018, McKinsey 2016, Arup and EMF 2018, Lejerbo et al. 2018). My understanding of the concept comes from working on several projects for GXN during 2016-2018, including interviews with 25 stakeholders in the Danish construction sector to identify barriers and opportunities, and contributing to Arup and EMF 2018, 2020 GXN & MCG 2018, Jensen and Sommer 2018.

fragmentation in project delivery, this poses serious challenges and circular economy remains a fluid concept; there might be agreement about the overall goal, but little consensus about definitions, means of realisation, and measures of success (Korhonen et al. 2018).

The contemporary understanding of circular economy, Casper explained, evolved through contributions from systems level approaches, which all share a focus on the interdependence between organisations and their environments[27]. This interdependence gives rise to a host of wicked problems. Designing and building in ways that allow cleaner products and better materials to circulate at high value for longer requires new partnerships in construction. Expertise, approaches, and business plans from all companies involved with a given product or process must be integrated to a higher degree than at present as no one company can hold all the expertise.

This expanding scope encapsulates a core condition of design work at 3XN and GXN, which involves interdisciplinary teams in the studio working with external collaborators to solve problems. For 3XN and GXN, questions of new approaches to design and technics are becoming questions of how an expanding circle of specialists can work efficiently together in ill-defined and shifting territory (Clausen et al. 2020). In a survey of 'collective intelligence' in design, architects Christopher Hight and Chris Perry posit that: 'Ultimately, innovative design does not concern the novel appearance of objects, but rather constructing new manifolds for the production of knowledge that transform the objects given by known tools and sets of practices.' (Hight and Perry 2006:9) The work of design teams in the studio of 3XN and GXN is deeply engaged with the creation of these 'manifolds,' what I have described as cognitive ecologies for collaboration.

In chapter 5, I discussed anthropologist Edwin Hutchins (2010) statement on cognitive ecology:

[27] This focus on ecological interdependence shares much with environmentally oriented architectural thought of the 1960-70s when circular economy was first being conceptualised (e.g. Boulding 1966). Notably Buckminster Fuller's (2008[1968]) *Operating Manual for Spaceship Earth*, and Stewart Brand's (1968-) *Whole Earth Catalog*. It also brings to mind the cybernetic environmentalism of anthropologist Gregory Bateson (1987[1972]).

> It is clear that the cognitive properties of groups can be quite different from the cognitive properties of any individual in the group (…) the patterns in the density of interconnectivity determine cognitive properties of the system whether the system is an area of a brain or a group of governmental agencies responding to a crisis. (ibid. 711)

Cognitive ecology offers an analytical framework for understanding the statement of Hight and Perry. Hutchins developed the concept cognitive ecology with particular attention to the interdependence amongst elements in well-defined system such as the bridge of a U.S. Navy Ship (1995a) or the cockpit of a plane (1995b). These examples were drawn from rigid social organisations with well-established procedures for collaboration around clearly defined problems such as navigating a ship safely to harbour or maintaining the right speed for landing a plane.

Here, I will explore how cognitive ecologies come to shape social mind in teams working under much more loosely structured organisation to understand how the collaborative practices of design can become scaffolding for social extension of mind. In Section II, I discussed the notion of cognitive ecology to analyse how modelling software enables teams to work with complexity at a human meaningful scale. The present section focuses on social interdependencies in this work, and how cognitive ecologies bring together technics, people, ideas, and knowledge to transform the possibilities for collective practice and social mind at the studio of 3XN and GXN.

7.3 Cognitive ecology and patterns of interaction

In his work on cognitive ecology, Hutchins (2010, 1995a, 1995b) recommends looking out for how specific patterns of interaction change cognitive properties of an organisation. This is what I will do after a brief description of the background to the *Circularity Lab* project.

The idea of creating a full-scale pavilion to showcase circular design and construction originated within Arup, the Ellen MacArthur Foundation, a charity focused on circular economy transition,

and Google. Both Kasper, the founder of GXN, and I had met with Arup and the Ellen MacArthur Foundation on separate occasions to discuss possibilities for collaboration; ideas for bringing 3XN and GXN into the demonstrator project began to take form in spring 2017.

Skype calls, emails, one-pagers, and tentative time plans were exchanged between Arup and GXN during spring, but until late summer 2017 there was no detailed and agreed upon goal for the project, no public name to call it by, and most of the project team had yet to be in the same room to discuss their ideas. This finally happened across two August days in 2017 at Arup's New York offices in Lower Manhattan. The kick-off meeting for the project brought together representatives from the project partners Arup, Ellen MacArthur Foundation, Turner Construction, Google, as well as Kasper and me.

As Kasper explained to me on our way to New York, it was essential to give the project a strong architectural concept and design in a bid to find funding for its construction. Funding was to be found amongst material suppliers, who could use the pavilion to showcase innovative products and their commitment to a greener construction industry[28]. While the project was exploratory at this early stage, the prospect of creating a pavilion with leading partners in their fields, had generated considerable excitement in the GXN team, and Kasper had secured commitment from 3XN's Competition department to help with design work. But first we needed to find out what the project partners wanted from the pavilion, and we needed to develop a design brief to communicate this to the 3XN and GXN design team which would be tasked with expressing these goals in architecture. In my notes from the trip to New York, I have taken this down from Kasper: 'These things require love, the fundamental attraction of design is a super important driver for the project.' When I brought this up in a chat with him at a later stage, he explained that the power to reconfigure complex problems into new aesthetic and functional solutions is a key promise of design; in this

[28] At the time of writing, the project partners have put construction of the demonstrator on hold due to lack of sponsorship funding required for its creation.

way early design work turns wicked problems on their head through creation of design concepts that can show a way through complexity for projects.

Establishing a shared cognitive ecology for the project

The point of an architectural pavilion or demonstrator is to somehow demonstrate, inspire and influence; to make emerging ideas graspable and convert the sceptics. As Kasper explained to me on our way to New York, defining a focus and design brief for the pavilion required clarification within the project team of its essential message to the industry. The *Circularity Lab* kick-off meeting therefore encapsulated the problems of interdisciplinarity, collaboration, and the creation of collective meaning which I have discussed so far in this chapter. In our talk before the New York meeting, Casper, one of GXN's experts on circular economy and design explained it like this:

> Construction is an old industry, it is very conservative, and there are a lot of actors. There is no one stop shop you can ask to do a building for you. I am an architect; I can draw a building for you. I cannot make bricks. I cannot make mortar. I cannot build it. It takes many different actors to make a building. This is a challenge. As architects we are not used to speaking to the demolition company that will take the building apart. There are a lot of gaps in the process and we need collective thinking if we want to change the industry.

The kick-off meeting in New York was about this type of collective thinking. It was about establishing a shared cognitive ecology (Hutchins 2010) that would allow a team of different actors to work efficiently on design and construction challenges for the still rather loosely defined question of what circular economy in the built environment might look like. To this end, sharing of ideas and expertise within the project team is obviously important, but as Douglas (1984[1966], 2003[1973], 1986) has pointed out, so is the social contextualisation of this information through collective creation of meaning. While all the project partners at the meeting had agreed on the prospect of creating a full-scale circular pavilion, much remained to be defined. Not least the details

of what this pavilion was supposed to do. What exactly was it supposed to demonstrate? Who were the audiences? How should it look and feel? Where was the site?

Current uses of the term circular economy cover a diffuse set of meanings (Korhonen et al. 2018, Kalmykova et al. 2018). At the New York meeting were some of the people who had already taken steps to define the meaning of circular design and construction through projects within their organisations. I will argue, however, that the wicked problem of 'circular economy in the built environment' looks different to an engineer concerned with construction techniques, an architect preoccupied with concept design, or a technology company with a large real estate portfolio. Different expertise reframes the problem of circular economy in subtle ways and the creation of a shared cognitive ecology was essential for efficient collaboration on the *Circularity Lab* project.

Analytically, cognitive ecology highlights the mutual dependencies between disparate elements in an ecosystem. Hutchins (2010:711) recommends tracing *patterns of connectivity and interaction* between elements in the ecology to understand how it works. My analysis of the *Circularity Lab* kick-off meeting will focus on how patterns of connectivity and interaction were established by the project team, and how these patterns allowed the team to re-work ideas and merge expertise into shared meanings. The argument is that different meeting formats and materials, such as presentations, workshops, and discussions, engendered different patterns of interactions whereby new shared understandings of both the central problems of the project and their solutions could emerge. That different meeting formats facilitate different interactional dynamics should not be controversial to academics who routinely sit through keynotes, plenaries, panels, lunch discussions, and perhaps a breakaway to the pub during conferences, but let us return to the *Circularity Lab* kick-off meeting to explore this argument in more detail.

Patterns of Interaction 1: partner presentations

The meeting took place in a 5th floor conference room in Arup's lower Manhattan offices. On the first morning of the two-day meeting, executives from the project partners presented visions for the project and argued for how it might fit into company strategies. These presentations focused on why the partners had engaged with the project in the first place, as well as what they knew about the challenges of circular design and construction from prior projects.

Presentation contents

After a welcome and introduction, we had three partner presentations of visions for the project that all focused on business impacts of circular economy in real estate and the need for developing frameworks that could support reuse of products and materials in construction. At these presentations the stated goal of the demonstrator was to provide opportunities to test specific construction and material applications before deciding on economic frameworks for scaling up successful approaches.

These presentations were followed by discussion across the table about what these goals entailed for the project. These discussions led to agreement amongst the partners that demonstrating circular economy required building something that actually was circular rather than creating a mock-up; the building should be designed for disassembly and with sustainable materials, which could be re-circulated after use. This additional goal had wider consequences as the team agreed that it became important to involve material suppliers in the project in order to advance their understanding of business opportunities in circular construction. And this in turn introduced concerns about construction principles, material supply chains, and recycling infrastructure into the project.

After each presentation, the team discussed goals stated in the presentation: exploring business potentials of circular economy, developing frameworks for reuse of construction materials, and

involving a wider supply chain in creation of an actual circular pavilion. These discussions explored practical implications of the goals from the respective fields of expertise of each individual partner.

Through these presentations and discussions, the team arrived at four specific circular design and construction challenges for the project: 1) identifying circular supply chains for building components; 2) getting suppliers to take back products once the demonstrator was demolished; 3) exploring possibilities for reusing upcycled materials; and 4) designing and building for disassembly.

After lunch, the team's engineering partner presented insights from a prior circular pavilion, which had been completed by them. This presentation focused on construction and supply chain challenges with sourcing products for the demonstrator, but also noted the need to create something which could appeal to the general public and not simply the construction sector in order to expand the scope and impact of the project. In the discussions following this presentation, the team began expanding their focus from technical and supply chain concerns to thinking about which public experiences the demonstrator might facilitate. In these discussions the partners began probing the ability of circular economy in the built environment to enable quality of life in cities, and how this might be turned into engaging experiences for the public. One partner suggested that the pavilion should showcase local businesses working with circular economy, another that it should be moveable and follow large-scale events in the city, another that it be rented out via Airbnb to provide people with the chance to live and work in a circular building.

Patterns of interaction

In this way, early presentations at the meeting set the scene for discussions that followed; while these discussions were open-ended, the one-sided format of initial presentations was crucial for sharing partner goals and insights which would come to both frame discussions and be modulated

by them. The interactional pattern of the presentation format focused attention on one speaker at a time, aided by slide decks with key talking points, graphics, images, and videos. This facilitated concentration and the communication of key goals and points from the individual partners.

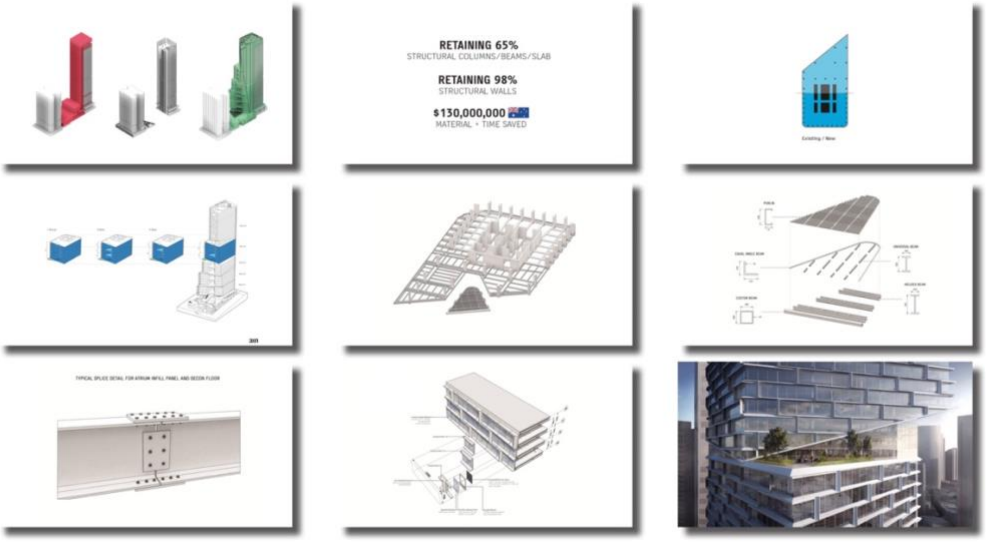

Fig. 7.2. Kick-off Meeting day 1, slides from Kasper's GXN presentation focusing on design for disassembly principles developed through ongoing design research and architecture projects.

While project partners from different fields of expertise presented what they perceived as core goals and challenges for the project, the presentation format itself helped introduce key elements for collective sense-making. These elements were in the form of the goals introduced and discussed and the expertise and experience shared during these discussions.

Screens and slide decks focused attention for the presentations. Digital images, renders, and models anchored ideas and added context to abstract concepts, making them easier to grasp (fig. 7.2). Presentations shared by individual partners served as raw material for discussion; the totality of goals, images, and videos, became a rich background that participants could probe, convert, and synthesise anew during these discussions to begin clarifying project goals. Rather than discussing the challenges of creating a circular building in the abstract, pictures of construction systems and

experiences with suppliers from actual projects helped the team focus on technical aspects of the challenge in front of them. In this way, the presenters could carve out a precisely formulated stance and introduce specific elements into the emerging cognitive ecology.

These elements included goals, such as exploration of supply chains and economic frameworks or the creation of public awareness, as well as technical challenges and know-how from specific fields such as construction, supply chain management, material upcycling, and design for disassembly. They included both domain knowledge in the form of assessments of circular economy's potential impact in construction, and structural knowledge regarding the inner workings of projects and how these had managed to meet some objectives while falling short of others. The mixing of domain and structural knowledge from across different fields of expertise helped the team collectively define the meaning of the contested term 'circular economy' for the project.

Patterns of Interaction 2: design workshops

The cognitive ecology established at the kick-off meeting for the *Circularity Lab* project relied on more than sharing of separate partner perspectives. New interdependencies had to be forged between people, information and materials for collective cognitive properties to emerge in the group (Hutchins 2010:711). For this, the ideas and insights introduced in partner presentations had to be transformed through social interactions that created new couplings between people, ideas, expertise and knowledge in the cognitive ecology. Advancing beyond early goal setting for the project to a clearer understanding of its content and organisation required different interactional patterns. GXN led two design and ideation workshops in order to establish visions, values, and programmatic uses for the demonstrators, which could form a loose brief for the 3XN and GXN design team when Kasper and I returned from New York to Copenhagen.

Workshop content

One workshop sought to probe the vision and values for the project by inviting participants to share and collectively elaborate on use-cases for how circular economy could play out in everyday life. Another workshop sought to facilitate a discussion of aesthetics, programmatic uses, and structural needs by exploring different typologies for architectural pavilions.

The first workshop was kicked off with a brief slideshow by Kasper. This provided real examples of upcycling such as sports shoes made from ocean plastics and the use of old jeans for acoustic insulation in buildings, before presenting a series of speculative juxtapositions of well-known companies such as Spotify, Airbnb, Goldman Sachs with a series of questions (fig. 7.3): what if you could subscribe to the latest fashion (Spotify)?; what if your house could grow with your family (Airbnb)?; what if a façade could be part of your savings for the future (Goldman Sachs)?



Fig. 7.3. Kick-off Meeting day 1, slides from GXN framing of the first workshop presenting what if scenarios for how circular economy and services could become part of everyday life for users.

These slides, which we had prepared on the way to New York, were rapidly thrown together and deliberatively crude in their juxtapositions. As Kasper explained while we were coming up with the juxtapositions sitting in a 7-Eleven in the Copenhagen Airport, the goal was to prod project partners away from their own domains of expertise in real estate, engineering, and construction systems, to begin to think about the underlying values and visions for the project. The deck should help project

partners imagine real and speculative use cases for circular economy in day-to-day life, with the aim of using these to define core values for the design brief.

The presentation was followed by 30 minutes of team-based discussion in smaller break-out groups to come up with engaging examples of circular lifestyle. The break-out groups came up with a series of real and imagined use-cases, which they shared for the final 30 minutes of the session. These included a newly minted start-up for furniture leasing, imagined and existing maker spaces in New York, community-based clothes and meals sharing programmes, and an existing Brooklyn based brewery reusing discarded bread for beer. While these examples might seem far removed from design and construction, their subsequent discussion in the project team helped define core values for the design brief. Specifically, the team agreed that a focus on local and communal aspects of circular economy were part and parcel of creating a demonstrator that resonated with the wider public. Building on this, the partners further decided that the demonstrator should provide a space for connecting people by enabling communal events about circular economy in everyday domains such as food, fashion, and work.



Fig. 7.4. Kick-off Meeting day 2, slides from GXN framing of the second workshop focusing on pavilion typologies and architectural examples.

The second workshop, which GXN ran on the second morning of the meeting, followed a similar format. An initial presentation by Kasper focused on pavilion typologies and examples, including tensile structures, inflatables, advanced structural systems, and at the other end of the spectrum, stacked containers (fig. 7.4).

These were presented with examples of actual pavilions and diagrammatic sketches of how they were put together. Following this, we asked the project partners to define what they liked and did not like about these pavilion examples during a 45-minute plenary discussion. While the team talked Kasper was sketching out ideas on a large flip board at the end of the table (fig 7.5).

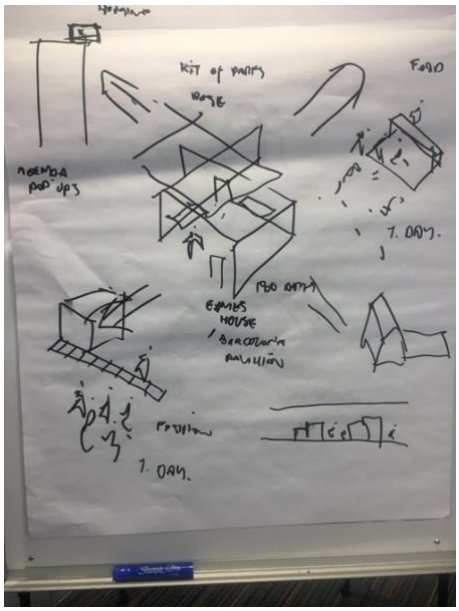

Fig. 7.5. Kick-off meeting Day 2: GXN documentation, developing ideas for the kit of parts and potential pop-up pavilion typologies during plenary discussions.

During these discussions, the project partners defined a series of core programmatic and structural needs for the pavilion. Keeping in mind the need for involving and connecting local communities, which had been defined during the workshop on the first day, the team decided that the pavilion should be made from a flexible kit of parts, which would enable construction of both a primary structure and potential pop-up pavilions for localised thematic events. The team's structural

engineers and construction experts defined functional needs for these systems, as well as the merits and drawbacks of potential sites of construction for the pavilion and its pop-ups. The team also discussed the 'feel' of the structures which should not be experienced as rickety or too temporary, but had to have a feel of permanence, adaptability, and flexibility about them.

Patterns of interaction

The design workshops focusing on circular use cases and pavilion typologies facilitated different interactional patterns when compared to the partner presentations of the first morning. These workshops did not highlight any one speaker, but distributed attention through series of open-ended questions and responses, which facilitated turn-taking in rapid succession involving everybody around the table. The question-driven framing of ideation sessions set the stage for other patterns of participation. Alternating between smaller break-out sessions for debating questions and plenary discussion of responses allowed for a large number of ideas to be developed, shared and evaluated.

Rapid turn taking between people and ongoing documentation via flip boards, sketches, and drawings both distributed and focused attention allowing participants to build upon each other's ideas. When engineers discussed structural merits of different construction systems Kasper could sketch out the basics of these (fig. 7.5) allowing the team to evaluate them against goals such as adaptability, programming, and feel. Based on these interactions, a shared understanding of the interdependencies between project vision and programmatic and structural needs could emerge.

Presentations of use cases during the first workshop came with normative assumptions that subsequent discussions helped clarify into a more coherent vision for the project within the team. This introduced community aspects of circular economy alongside more technical and structural concerns. Workshops facilitated collective reasoning, the introduction and evaluation of different

perspectives on the meaning of circular economy in the built environment, which in turn helped contextualise and modulate the goals introduced in initial presentations.

Through these interactions between the project partners, the wicked problem of 'circular economy in the built environment' evolved from primarily an engineering and business challenge to becoming a design challenge incorporating concerns about people's experience of form, storytelling, and identity. The emerging conception of circular economy, which would be used to form a brief for the 3XN and GXN design team, married program, form and construction systems, local identity and global supply chains, lifestyle and business development. From a design perspective these juxtapositions create rich possibilities for further ideation and modulation.

7.4 Participatory sense-making

My argument throughout this chapter has been that the meaning of wicked problems in architecture is not to be found 'within' the problems, but rather in the shared process of presentation, probing, and modulation, which surround their clarification by design teams.

The *Circularity Lab* kick-off meeting shows how design projects are necessarily distributed and collective as no one person can hold all the information needed to make a functioning and aesthetic building. While there were experts on modular construction, supply systems, design for disassembly, communication strategy, public policy, and architecture at the meeting, no one person in the team could possibly be an expert on all these subjects at once. And no one domain of expertise could have conceptualised the brief that emerged from the meeting as this incorporated both project partner goals, aesthetic qualities, technical requirements, event planning, and evaluation of different potential sites in New York. In this way, the creation of shared goals, values, and contextualised needs for the project's design brief implies the necessity of a shared cognitive

ecology to enable collaboration and socially extended mind. The meeting brought together and mixed different forms of expertise. Its discussions integrated both domain knowledge in the form of codified assessments of circular economy's potential impact in construction, and structural knowledge regarding the inner workings of actual projects and construction systems. These types of knowledge were brought together through different patterns of interaction between people, materials, and ideas, what I analyse through the framework of cognitive ecology.

Compared to the practices of naval navigation or air traffic control outlined by Hutchins (1995a, 1995b), the interactions described above are less rigid, but they are still contained in well-known formats of presentations, slideshows, discussions, and design workshops. In the less rigid organisation of the design team, cognitive ecologies are made and remade through situated interactions between people which are given meaning by institutionalised behavioural formats and a rich interactional context of visuals, technics, sketches, embodied cues, memory and affect. The emergent meaning is social and predicated on the rich possibilities offered by different interactional dynamics and contexts.

Patterns of Interaction 3: participatory sense-making

Cognitive scientists Hanne De Jaegher and Ezequiel Di Paolo (2007, De Jaegher et al. 2010) have advanced the notion of *participatory sense-making* to explain how social interactions come to shape social mind. De Jaegher and Di Paolo define *participation* as:

> the regulated coupling between at least two autonomous agents, where the regulation is aimed at aspects of the coupling itself so that it constitutes an emergent autonomous organization in the domain of relational dynamics, without destroying in the process the autonomy of the agents involved (De Jaegher and Di Paolo 2007:8).

With regards to 'regulated coupling … where the regulation is aimed at aspects of the coupling itself,' we have seen how different institutionalised meeting formats, such as presentations,

roundtable discussions, and design workshops, come to constitute interactional dynamics through the regulated patterns of coupling they engender between people. These social patterns are akin to what De Jaegher and Di Paolo call an 'emergent autonomous organisation in the domain of relational dynamics.'

Similarly, the 'autonomy of the agents' throws light on the relationship between expertise brought into the cognitive ecology by the different project partners during the two-day meeting and the collective meaning created through the meeting itself. While the subject-specific expertise of individual partners, such as modular construction or design for disassembly, was not necessarily transformed in the meeting, the cognitive ecology of the meeting itself was transformed by this expertise. Domain and structural knowledge from engineers, architects and construction experts was central for establishing the practical meaning of the concept of 'circular economy in the built environment.' This knowledge became crucial for establishing and modulating shared meaning through participatory sense-making in the sense forwarded by De Jaegher and Di Paolo (2007:9). Participatory sense-making mixed domain and structural knowledge, codifiable insights and tacit know-how and intuition into the emergent cognitive ecology, which thereby included interactional dynamics that enabled participation and social extension of mind. In turn this enabled social creation of meaning in the form of a rudimentary design brief for the project that included business goals, construction systems, aesthetics and experiential aspects..

Patterns of Interaction 4: approximation and interpretative flexibility

Back in Copenhagen, the 3XN and GXN design team set to work creating an answer to this brief. During this work I interviewed Enlai, an experienced architect and researcher with the team. His insights can help further the argument that in the social situations of design, the sum is bigger than its parts. Enlai explained:

> Let's say, you come up with a form, and you don't know whether you love it or hate it. Another person sees a potential in that form. You have a discussion that allows you to see different values … it allows you to see their point of view, and by seeing their point of view, you also see multiple points of view, even the ones that don't exist within the person you are talking to. That is what I'm talking about … because then there is your idea, their idea, and a third space idea. And usually it is the third space idea you fall in love with.

The 'third space idea' emerges as shared meanings are established and modulated collectively through processes of participation as argued above. Enlai's notion of 'falling in love' might not be too far of the mark when describing this type of collective ideation. Affective processes have become a focal point in discussions of social mind, and some philosophers of mind highlight how social mind relies on the full richness of people's interactions, including affect and emotion (Bower and Gallagher 2013, De Jaegher et al. 2010, Gallagher 2017:158). Matthew Bower and Shaun Gallagher (2013) argue that affect is crucial for directing our attention towards salient aspects of a situation, sometimes without our awareness. Affect arises from social interaction, they argue, through tacit awareness of other people's minimal embodied cues in the situation. Tone of voice, an inclination of the head, excitement around ideas, and other cues (or their absence) are indicators of the dynamics of a design situation (see also Rietveld and Brouwers 2016).

For Bower and Gallagher, social dynamics grow as we mirror each-others emotional cues in specific situations. Affective awareness helps us decode new situations by reference to prior situations with similar cues. It serves to anchor memory of institutionalised patterns of behaviour, not least through the anxiety connected to their intentional or unintentional breach (ibid 126). This intersubjective dimension of cognitive ecology is not fully theorised by Hutchins but becomes important for understanding how collective practice and social mind come to influence ideation and troubleshooting in the design studio.

The multiple points of view, which Enlai's notion of a 'third space idea' entails, show how participatory sense-making enables designers in a team to recognise emergent possibilities not present with each of them alone. This is crucial for creative ideation, as Enlai pointed out.

Cognitive and evolutionary scientist Michael Tomasello (1999) has argued that our ability to play with simultaneous perspectives on the same situation stems from an evolutionary adaptation that ties human mind inextricably to society. This adaptation enables us to identify with others as intentional beings, which in turn permits new forms of cultural learning through language, symbols, artefacts, and institutions by freeing human mind: 'from the immediate perceptual situation not simply by enabling reference to things outside this situation […] but rather by enabling multiple simultaneous representations of each and every, indeed all possible, perceptual situations.' (Tomasello 1999:9)

By seeing the world as others might see it, we multiply our representations of any given situation. In Section II, I argued that attending selectively but skilfully to the digital materiality of different digital design environments gives architects effective means of dealing with the ill-defined problems of design. Discussing design of the *Circularity Lab* demonstrator with Enlai, it also seems digital sketches and models come to facilitate synthesis of collective perception and imagination in much the same way described by Tomasello. Enlai explained it like this:

> You have to be as efficient as possible, and you do that by *approximations*. For two reasons. Number one is that everybody who has been around a design work environment understands that it is often quite effective to do this fail-fast sort of mentality where you basically hash together an impression. The *lack of specificity allows other people to have their interpretations*, so the process of creating fantasies with freedom for interpretation is the other reason why you would not try and define something to the point where it looks like a result. (My emphasis)

Approximation, the sharing of emerging ideas through rapidly cobbled together digital images, sketches, and models, allows other people to be enticed into shared creation of meaning through participatory sense-making. These approximations are available in GXN's design logbooks for the

Circularity Lab project, which show how the design concept evolved as Enlai and the 3XN and GXN team worked through ideas in winter 2017 and spring 2018 (fig. 7.6).

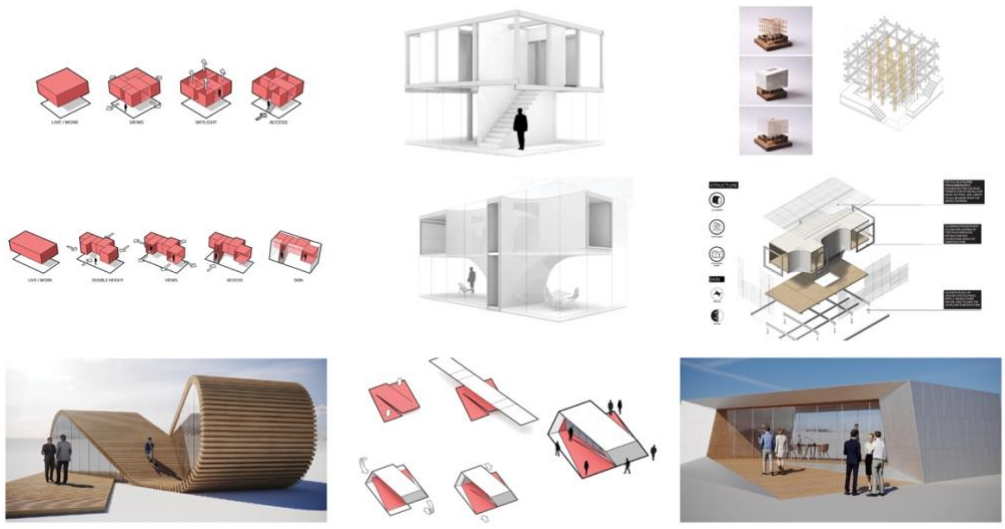

Fig. 7.6. Evolution of design concept for the Circularity Lab as Enlai and the 3XN and GXN team worked through ideas, winter 2017 – spring 2018.

Approximations and participation allow for shared meaning to be created and modulated through processes of social mind. We saw examples of this in the analysis of the design workshops in the *Circularity Lab* kick-off meeting where a few initial and very rudimentary juxtaposition of companies, services, and questions set the project partners off on divergent interpretations of possible circular economy applications in everyday life. We also heard Enlai explain the subsequent processes of design through a similar focus on participation and sharing of ideas, and we can see the evolution of these shared ideas through images from the project's logbook and renders of the final design (fig. 7.6 and 7.7).



Fig. 7.7. Renders of the *Circularity Lab* design, summer 2018.

Shaun Gallagher (2017:80) has described how the interpretative flexibility inherent in participation entices collective action: 'I see the other's action as inter-actionable or as calling forth a response on my part.' This 'calling forth' is also analysed by Eric Rietveld and colleagues in their discussion of skilled intentionality: 'Our learning history and our skills show up in the way the world solicits action. A skilled architect, for example, is simultaneously sensitive to several relevant aspects of the environment and is moved to improve her grip on the situation as a whole.' (Bruinberg & Rietveld 2019:200) Rietveld thereby point to the importance of our learning history in recognising and responding to salient social affordances of a given situation, extending the timescale beyond the immediate interactions forwarded by Di Paolo and De Jeagher, and linking design to Gallagher's wider argument for affect and social learning.

As argued by Tomasello (1999), interpretative flexibility spring from a basic interpersonality of mind; social interactions mediated by cultural production becomes key for collective cognition. Following Douglas (Douglas and Isherwood 1996[1979]:38) we might say that social interactions – with people, materials, and objects – serve to make visible the categories of culture, thereby enabling people to enact specific interactional patterns and enable sociality of mind (see also Gallagher 2017:80). This points to the role played by socially shared and enacted institutions in the form of meaningful patterns of behaviour for creating a context for participatory sense-making. During definition of the *Circularity Lab,* institutionalised patterns of interaction in the formats of

presentations, roundtable discussions, and workshops and the production of ideas, visuals, and sketches were all elements of cognitive ecology for the project. Gallagher (2017:78) suggests that we grasp each other's intentionality in terms of its appropriateness in specific situations. Thinking of the interactional formats inherent in presentations and design workshops, it should be clear to anyone with a passing experience of these that wildly firing away ideas while your boss is presenting will not get you promoted; and similarly that taking up time to lecture during ideation workshops is poor form.

To some extent we might say that presentations enable hierarchical interactions, and workshops more networked interactions. These different interactional dynamics enable different practices at different stages in the design process. Nearing the end of our interview about the design process of the *Circularity Lab*, Enlai explained:

> There are different sorts of design processes and in many cases, like what I'm working on now [the Circularity Lab], at a certain stage it is good to have a very strong hierarchy. Because it makes everybody's lives easier, even the people at the bottom, if they have a clear set of decisions and they follow those decisions. It removes doubt and allow people to work more efficiently. But in the part where you are creating options, then it is extremely helpful, and I think it is beneficial for everybody on the team, to be able to design for personal investment. A more de-hierarchised situation allows certain concepts to bubble to the surface.

We can begin to see from this quote how interactional patterns of participatory sense-making are embedded in larger institutional contexts and become meaningful by conforming to specific organisational dynamics. The coming chapters will discuss the make-up of these institutional contexts in the studio of 3XN and GXN and how they interact with the digital materiality of different design software.

Conclusion to chapter

Douglas invited us to explore social creation of meaning by analysing the richness of human interactions and material culture (e.g. Douglas 1984[1966], 1986, Douglas and Isherwood 1996[1979]). Following this thread via design theory and philosophy of mind, we have seen how shared meaning is created in design teams via shifting patterns of social interaction. I have argued that these patterns become constituent of social mind in design teams, and necessary for merging different expertise found as both domain and structural knowledge in a team of collaborators.

Investigating processes of participatory sense-making (De Jaegher and Di Paolo 2007) through definition and design of the *Circularity Lab* project has shown the dependencies between design concepts and design contexts in architecture. It has shown that the formulation of and response to wicked problems in design is vitally dependent on the social contexts in which this happens. The co-development of concept and context constitutes evolving cognitive ecologies (Hutchins 2010) that enable social mind for design teams. These are anchored in digital materials such as presentations, sketches, and models.

In Section II, I argued that cognitive ecologies in the studio of 3XN and GXN are entangled with the digital materiality of design models and scripts that allow designers to mix expertise and knowledge from different partners into new designs while being selective about the relationships tested and brought forth at any one time. In this Chapter, I have argued that not only materials and technics, but also social interactions, and larger institutionalised patterns of collaborative practice, form part of cognitive ecologies and social mind in design teams.

Douglas reminded us that: ‘There can be rules without meaning, but no meaning without rules. This drove the study of meaning straight to the study of social relations.’ (Douglas 2003[1973]:9) In the following chapters I will discuss these rules, understood as institutionalised patterns of collective behaviour, as well as the digital materiality through which they are stabilised.

Chapter 8: Project

'Watching this mock-up, it is so obvious that it has been through a long process, which is what has made it so damn sharp.' In early winter 2016, Kenn and I were talking about his work on the 3XN designed headquarters for the International Olympic Committee (IOC) in Lausanne, Switzerland. He had suggested we develop a paper for the 2017 Design Modelling Symposium[29] to be held in Versailles in April and we were trying to clarify our focus. Sitting in one of the studio meeting rooms, we were looking at the room's large flat screen monitor to admire the latest pictures from the IOC building site (fig. 8.1). The construction team had just finished a full-scale mock-up of the building's façade, and Kenn was happy with the result. Arriving at this level of detailing, he explained, visibly excited about the product, had taken a lot of teamwork and problem solving.



Fig. 8.1. Rendered output of the IOC façade (left). 1:1 mock-up of the façade design (right).

The problem outlined in this chapter is twofold; on one side, we find the question of how teams at 3XN and GXN work to resolve design problems during the lifetime of architecture projects; on the other, the issue of how personal expertise built up through years of design research (see Ch. 6)

[29] The 2017 *Design Modelling Symposium* is one amongst a number of academic and professional conferences for Digital Architecture I attended with the GXN Digital Design group. Others included Shape To Fabricatation London 2018, Innochain Copenhagen 2018, AEC Tech New York 2019.

is meaningfully integrated into collaborative processes. I came to explore this problem in detail during interviews and discussions for the paper Kenn, Morten, and I eventually presented at the 2017 Design Modelling Symposium (Poulsgaard and Clausen 2017). Drawing on this paper, I here present 3XN and GXN work on the IOC Headquarters. I discuss the development of the project in the studio, including practices for coming up with and evaluating a large number of concepts during competition design, and for solving structural problems while managing construction processes during project development.

The work of anthropologist Mary Douglas takes as starting point that one of the key problems of social life is the collective definition of meaning from the incoherent flux of events surrounding us (Douglas and Isherwood 1996[1979]:43). In Chapter 7, I discussed how processes of participatory sense-making (De Jaegher and Di Paolo 2007, De Jaegher et al. 2010) allow architecture teams to collectively define meanings of the wicked problems (Rittel and Webber 1973) posed by architecture projects. This discussion showed that design work at 3XN and GXN is a collaborative practice, embedded within cognitive ecologies (Hutchins 2010) that enable socially extended mind.

I discussed examples of participatory sense-making during concept development and design of a GXN research project, but I argue that this type of collaborative work, and hence social mind, is a prerequisite for teamwork across the departments of 3XN and GXN. Architectural design is as intensely social in 3XNs Competition and Project Development departments as it is in GXNs research projects. Examples in this chapter will show that wicked problems, which cannot be solved by any one person alone, abound across all phases of architecture projects. The meaning of these problems must be collectively defined, and their resolution requires merging of expertise from an array of skilled individuals.

This chapter will expand the temporal scale beyond situated practices of participatory sense-making to the full lifespan of architecture projects in the studio. It will do so by discussing the

development of the new IOC Headquarters from competition to construction. The project was won by 3XN Architects in a high-profile competition in 2013-14 and construction finished in summer 2019. Site pictures from August 2018, show the full size of the building, red steel frames and curving concrete standing out against the green backdrop of park and lake (fig. 8.2).



Fig. 8.2 IOC Site Photo, August 2018.

In June 2019, when the IOC Headquarters opened to the public, the steel and concrete skeleton was concealed beneath high performing glass facades, and the process for how the building got there was effectively hidden. But during my time at the studio, while the project was still ongoing, architects at 3XN and GXN were excited about their work and keenly discussed the details that had taken them this far. Developing our 2017 paper on the IOC project provided an opportunity for interviews with key architects, alongside studies of competition materials, digital models, and a host of models, sketches, images, and drawings related to the project.

8.1. Olympic House I: Competition

In 2013, the IOC celebrated its 100th anniversary in Lausanne and launched an open architectural competition for a new headquarters in the Swiss city. Since 1968, the IOC has resided in the Château Vidy, a 18th century manor house in the Louis-Bourget Park by the shores of Lake Geneva. The chateau dates from 1774. In May 1800 it paid host to Napoléon Bonaparte before his famous passing of the Great St Bernard Pass. It was classed as a historical monument by the canton of Vaud in 1971. With the architecture competition, the IOC wanted to expand their headquarters in this historic setting with a new building and campus that could assemble 600 employees from various representative and administrative functions in one place (see IOC 2019).

The Olympic House competition was launched with a call for candidates 28 March 2013; when the competition judges of internationally established architects, representatives of the city of Lausanne, and IOC members met in June, they had 114 applications from five continents in front of them. From these, 3XN Architects prequalified for the IOC competition alongside 11 international architecture studios, including Toyo Ito and Associates, OMA, and Farshad Moussavi Architecture.

Concept design

Concept design is integral to defining an architectural answer to a brief and a key activity in competition projects. Competition architects, I spoke to during my time at the studio, all explained that for 3XN searching for a project concept is a way of interpreting requirements set out in the brief via design research, form-giving, and storytelling (see also Weiss 2017:189, Banke 2013:122).

During the four month long competition, the 3XN team worked through digital sketches, volume studies, and digital and physical models to develop an architectural answer to the brief. The team sat together in 3XN's Competition department and collaborated closely for the duration for the competition. When I first talked to Senior Partner and Head of Design Jan about the project, he

explained that the design concept was developed in recognition of the symbolism of the Games. The legacy of the Olympic games had acted as a design driver for the whole project, he explained while I scrambled to keep up with notes, but perhaps nowhere more recognisable than in 3XN's design for the large staircase referencing the well-known design of the five Olympic Rings in the central atrium of the building. Jan explained: 'For us the stair is a good story as we married symbolism with something practical. We turned the logo into something that very visibly connects all the floors and thereby embody the values of the project.' (fig. 8.3)

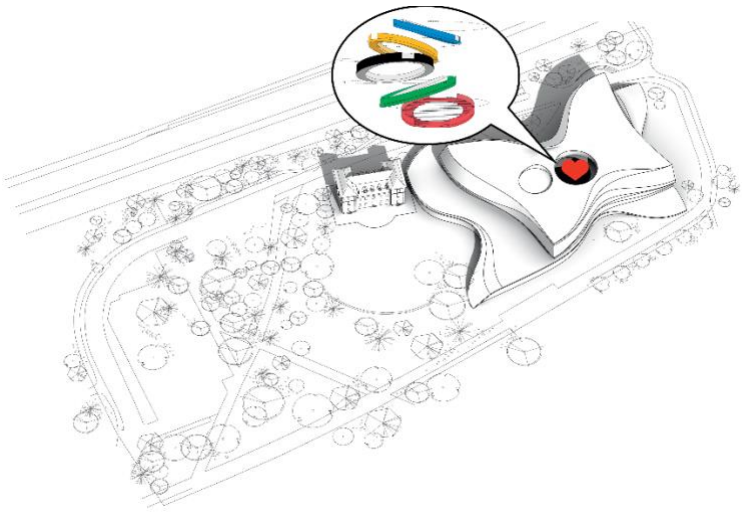

Fig. 8.3. IOC staircase in the central atrium referencing the five rings of the Olympic logo.

This combination of form, function, and storytelling is what the 3XN competition architects I spoke to told me they were looking for during concept design. When I interviewed Jesper, 3XN Studio Director and an experienced project lead from the Competition department, he explained that this was a collaborative process. While competition projects were driven by changing concerns, he explained, the task of the design team was to find the one thing which could: 'sort of crystallise the project for you.' He elaborated on how this worked in competition teams:

> For the first pitch we might come up with 100 different suggestions (…) we try to keep all opportunities open. It might as well be an intern who gets the right idea as the principal. It is

> important to get all the ideas on the table in this way, make them presentable and create a forum where we can evaluate them. And this is accessible to everybody.

In early competition phases architects sketch out ideas in parallel to present to each other – some creating 3D form experiments in Rhino design software, others parametric design tools in Grasshopper[30]. In this forum, Jesper explained, the hierarchy amongst individual architects is less of a concern than the ideas generated. And in fact, the initial design idea for the IOC staircase came from an intern in the Competition department. When I interviewed Laura, a digitally skilled architect who led design development on the IOC stairs, she pointed this out to me to emphasise the value of the intern experience for architects, and the importance of internships for getting new ideas and talented designers into studio teams and projects:

> I really enjoyed my internship here. And now I still try to remain connected to the interns we hire, and our process of getting them in, because I think *the intern experience is a really important part of how the office develops.* (My emphasis).

Jesper echoed this view in our talk. Pointing out the multitude of models from former 3XN projects that adorn the walls of the studio (see also fig 8.4 below), he explained how the models represented an accessible history of design at the studio, and the importance of communicating this to new interns and architects. The models show both finished projects and ongoing design studies and provide a freeze frame view of the design processes in the Competition department. Teams visit these models, Jesper explained, when their project leaders wanted to showcase or discuss forms and geometry from former projects to understand how they might work within current projects.

I saw this for myself, from my desk next to a large wooden model of a concert hall interior. Teams from the Competition department working on concert hall projects visited this model several

[30] See detailed description of these design software and their use at 3XN and GXN in Chapter 5, and a discussion of how digital materiality and social organisation become mutually supportive of specific institutionalised ways of working in Chapter 9.

times during my stay at GXN. They would stand around the model in a semicircle for anything from five to 15 minutes. The project lead would point out salient features of the design to the small group of listening architects. Details would spark series of questions and the team began to discuss these in relation to their current project, working out specific problems with reference to past solutions before heading back to work in front of their screens.

Here we can begin to see the important relationship between the studio environment itself, its models and materials, and collaboration in design projects. The idea for the IOC staircase did not emerge in a vacuum. Elaborately designed staircases and atriums are a design signature for 3XN Architects and have been central to several high-profile projects including Ørestad College in Copenhagen (2007), Nieuwegein City Hall in the Netherlands (2011), the UN City in Copenhagen (2013), and Segerstedthuset at Uppsala University in Sweden (2017).

Interns in the 3XN Competition department will either know many of these projects from before joining the team or learn about them from the architects they are working alongside on projects. As I will discuss below, this knowledge is not only transferred through teamwork in the communities of practice of the different departments in the studio (see Lave and Wenger 1991), but also circulate through digital scripts which are exchanged and reworked between projects.

While working on a competition in the summer of 2019, I saw first-hand how digital studio artefacts such as design models and logbooks become anchors for knowledge-sharing. This was a competition for a high-rise in North America. The team present at our start-up meeting consisted of the studio founder and creative director, a partner and two architects from the Competition Department, and me representing GXN. The start-up meeting was a three-hour affair where we went through digital logbooks[31] and presentations from recent competition projects while discussing

[31] A logbook template is found as a file within the generic project folders in the studio's shared drive. The format is encoded in InDesign, a popular desktop publishing software used ubiquitously at 3XN and GXN to manage layout of studio materials and booklets. This template helps organise files and materials, as the logs are continuously updated with relevant outputs depending on the research being carried out during the project's lifetime.

aspects from these which could be salient for the current project. We discussed ideas against the requirements we had each identified from reading the brief. One discussion centred on the brief's requirements to mix workplaces with amenities to attract high level tenants. Showing recent projects in Sydney and London, the architect running the presentation discussed how this requirement chimed with 3XN strategies of using atriums and double height spaces to break up the otherwise static floorplates of high-rises and create opportunities for varied programming. Taking over keyboard and mouse to call up on the screen a current 3XN high-rise project, the founder and creative director agreed but also urged caution by mentioning how fire regulations differed in the US compared to Europe and Australia. This meant that the developers on another North American project where 3XN had used this strategy had been cautious, though regulation and design had been aligned after much work. In the end it was agreed that the use of double-height spaces was important for creating a unique identity for the present project but should be proposed in a manner that highlighted structural opportunities for going without. This back and forth helped establish a common understanding of the project and its core values, recalling processes of participatory sense-making discussed in Chapter 7. After a number of these interactions, the meeting concluded with the agreement to create a shared logbook which would collect input from GXN and 3XN while the partner and two architects in the Competition department began to work on volume, form, and façade design to develop the concept.

Volume, Form, and Façade design

Volume studies, form, and façade design are core components of competition work at the 3XN studio. The volume and footprint of a building on a site determines the square meters available for the developer, and hence the economy of a project. The façade of a building encapsulates its design and is a vital part of concept, aesthetics and storytelling on projects.

When speaking to Senior Partner and Head of Design Jan about the IOC project, he told me that in order to develop the architectural concept with reference to the Olympic legacy, the competition team defined three core design principles for the project: *movement*, *flexibility* and *sustainability*. The architectural meaning of these principles was matured through weeks of collaborative design research into volumes, form and façades during the four month long competition. The output of this work is collected in digital logbooks of the sort I helped develop for the competition project mentioned above. These are digital files that collect whatever research goes into a project at 3XN and GXN.

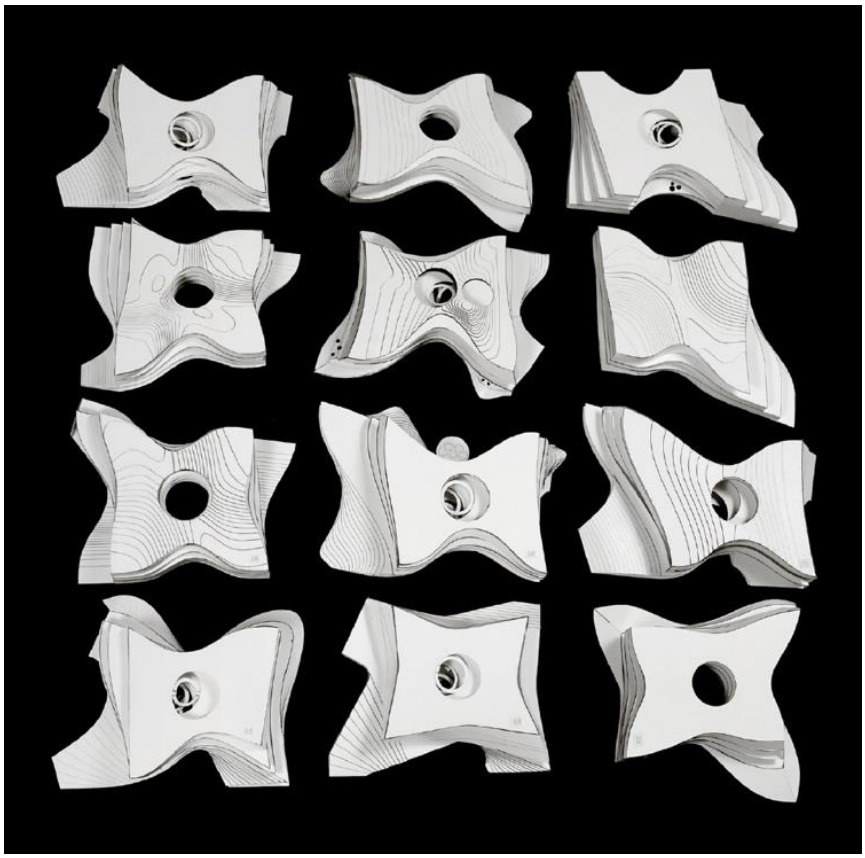

Fig. 8.4. Physical models of digital volume studies from the IOC project.

The logbooks for the IOC Headquarters show how design research during the competition included a large number of volume and facade studies. Volume studies are digital 3D models

created in Rhino to explore the possibilities of site, form, and layout of buildings. They are simple volumes, which can be generated quickly and in large numbers to understand how the requirements of the spatial programmes for specific buildings, spaces, and functions might be organised in a project. Physical models of selections of these volume studies still hang on the walls of the 3XN office (fig. 8.4). The volume studies in the IOC logbooks show how the Olympic logo, with its five rings, were referenced in early form finding experiments, for example through tests with five cylindrical volumes or five cylindrical cut-outs in more freeform volumes following the topography of the site and park. In later studies the rings come together in the central atrium and the volumes of the building begin to take on their current shape.

Later pages in the logbooks show visual research through collections of images connected to the Olympic games including collage-like collections of photos of athletes in motion such as dancers and snowboarders. In later logbooks the volume studies and Muybridge-like photos of athletes in motion become juxtaposed to help communicate the design language of the façade (fig 8.5). This clearly emphasises the design principles of *movement* and *flexibility* for the building, and several of these juxtapositions found their way into 3XN's communication of the project.

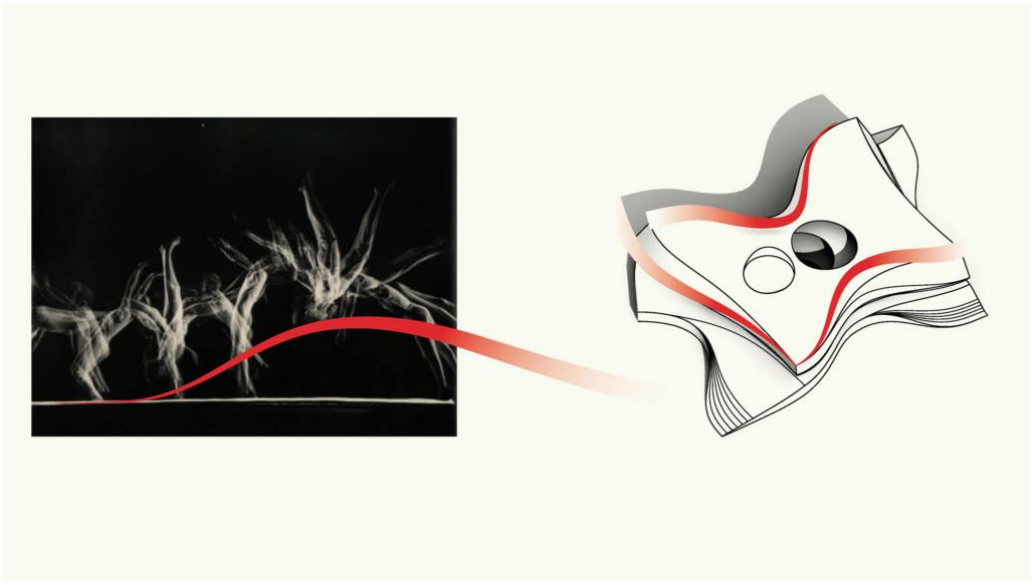

Fig. 8.5 IOC design and shape research.

In the competition logbooks several additional concerns show up to inform the development of the building volume and façade design for the IOC Headquarters. In our chat Jan explained how the specific aspects of the site nested between the Château de Vidy and the Louis-Bourget Park became a design driver. Ambitious energy and sustainability performance were another concern as the IOC was targeting the highest ratings in the sustainability standard Leadership in Energy and Environmental Design[32] (LEED). High flexibility of interior spaces was also a key concern; the building houses some 600 employees usually working in different offices and the team explored how to minimise structural constraints in the building to create an open and flexible working environment.

These aspects – relation to the park and Château, sustainability performance, flexible interiors with few structural constraints, and a dynamic design language – were developed in parallel during the competition. They came to inform the façade design in several ways, Jan explained. The competition design sought to merge building and landscape via a sloping façade rising from its surroundings. It proposed to move loadbearing structure into the façade itself to only have four load bearing cores within the building. Subsequently the open and dynamic design of the glass façade lead to the introduction of a *double-skin façade*[33] to meet performance and energy requirements.

On 31 October 2013, 3XN submitted its proposal in December 2013, after weeks of deliberation, the competition jury of architects, representatives of the city of Lausanne, and IOC Members chose three 'architecture competition laureates', who were invited to elaborate their ideas. These three were Farshid Moussavi Architecture from the United Kingdom, Xaveer De Geyter Architecten from Belgium, and 3XN Architects. Additional development in the extended competition gave the 3XN team time to further elaborate on design for the façade and the functionality of the building. In April

[32] The building is today certified LEED Platinum with a score of 93 out of 100, currently the highest scoring building in the new LEED v.4 rating system.
[33] A double-skin façade introduces an inner and outer glass layer in a connected faced to improve energy performance by having an insulating layer of air in between the two facades (see more about this on the IOC project below).

2014, the IOC Executive Board chose 3XN as the winner of the competition, and 3XN partnered with a local Swiss architect to oversee construction of the building.

8.2 Olympic House II: Project Development

The IOC façade introduced a freeform geometry in answer to the design principles of *movement*, *flexibility* and *sustainability* which were defined by the 3XN team during the competition. Architects in both Competition and Project Development told me that the project pushed the boundaries of 3XN's design language at the time. Once the competition was won in spring 2014, the studio was faced with developing and maintaining this design language while steering the project through development and construction phases.

Project Development at 3XN sees architects developing competition designs into buildable architecture with the stated goal being as high fidelity to the competition submission as possible, on time and on budget. *What You See Is What You Get*, is an explicit intention of the studio, presented on their webpage and referenced by several of the architects I spoke to. The 3XN Project Development department is responsible for producing the 3D Building Information Model (BIM) that structures this work during a project's lifetime, as well as construction documentation – the thousands of 2D drawings, plans, sections, and diagrams that are needed on site to construct the building.

Laura, an experienced architect who began her career as an intern in 3XN's Competition department and today mainly works in Project Development, explained:

> The competition often only has three or four views, a couple of plans, you know, the level of detail is not that far developed …. If I showed you what we showed for the competition and where we are at now, you'd probably say that it is pretty much the exact same; what have you been doing these last months!? But there is a lot of testing things out to find out what the

> competition concept means for structure and detailing. The goal is to keep it looking like the competition, but adding more detail.

On the IOC project this entailed ongoing digital design work using Rhino and Grasshopper with specific focus on the staircase and façade. In spring 2014, the work of developing and modelling the IOC façade began. This is where Kenn from GXNs digital design team got involved. When we first sat down in the winter of 2016 to develop our case study of the IOC project for the Design Modelling Symposium, Kenn told me that this was his first large project at 3XN. He had started at the studio in 2014 after several years working with digital design and modelling for a leading Dutch architecture firm. At 3XN, he quickly got involved in developing a formalised model for the façade of the IOC Headquarters. He explained the starting point handed over from the Competition team:

> It was freeform. As I could decode from the geometry this form was defined by twenty curves. Five curves for each façade defining a sort of rhythm. Always the five curves. Back then they were divided into points and then a surface was created between each curve to create these thin lines explaining were the glass should be. It was a glass box. It was segmented via some floor slabs, and that was it.

From these twenty curves, five for each façade, Kenn and the Project Development team developed the parametric model for the IOC project.

Parametric model

As described in Chapter 5, the core of parametric modelling is establishing explicit relationships between points in a 3D space to create the model. In digital models these points and relationships means that 3D geometry translates to data and data to geometry. Turning the freeform design of the IOC façade from the Competitions team into a formalised digital model, Kenn explained to me, required establishing this type of associative logic. Once defined, the logic would allow experiments with form and construction details without having to remodel the façade for every single iteration.

The façade model for the IOC Headquarters was first created using Rhino and Grasshopper. Kenn explained:

> We defined how we wanted the building grid. This was what we started with. We defined that we wanted to control the project using the twenty curves, because we wanted to maintain the core values defined in the competition. These are the curves: top and bottom of the façade and a kink in the middle. And then we have two waves running through the upper and lower half. So that is five for each side, describing how the movement of the façade manifests. This was how we could describe a dynamic form; the curves were creating the movement we wanted. Now we had points on the grid, and we had the form. So, we knew that if we began to pull one of the curves the whole thing would follow in a sort of chain reaction.

As he was speaking, Kenn drew a diagram in his notebook to show the five curves (Fig 8.6).

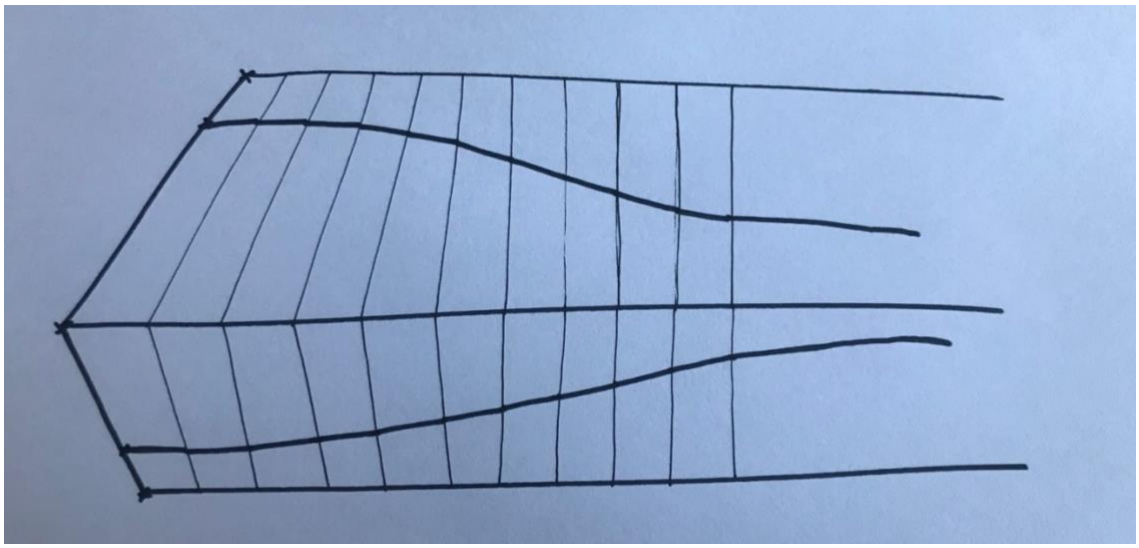

Fig 8.6 Kenn's sketch of the five facade curves for each side defining the overall façade design.

Modelling started from these five horizontal curves for each of the four sides of the building. While drawing, Kenn explained further: 'From using freeform curves as basis for the model, we could establish parametric links between curves and surfaces in the façade geometry.' Vertical lines connected points on these curves to create the surfaces of the façade with its variations in both horizontal and vertical planes (Fig. 8.7 and 8.8).

Within a few weeks, in the autumn of 2014, Kenn had constructed a flexible parametric model with input from the team, competition architects and the IOC project lead. The model formalised the competition design concept in a computational environment.

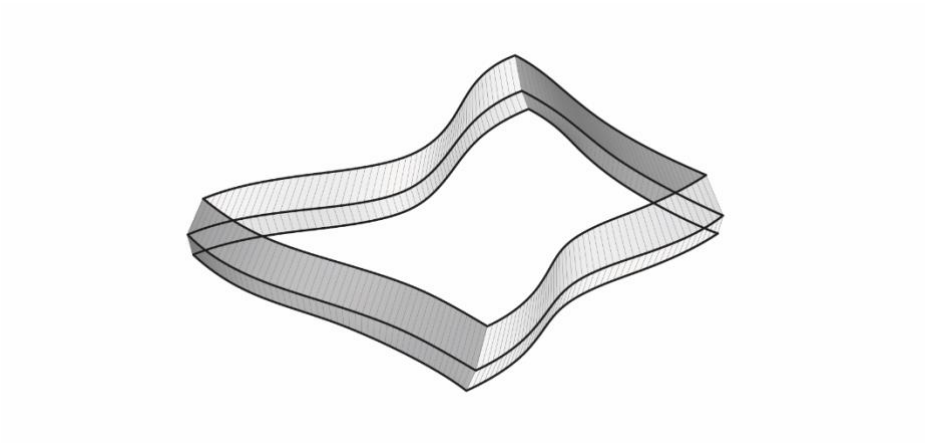

Fig. 8.7 vertical lines between horizontal façade curves show the design expression of the façade. Export from Rhino.

This would allow the Project Development team to test impacts of the overall façade design as construction details, such as loadbearing columns, glass-panels, and other façade elements were added to the model. Kenn explained that this was an absolute necessity as each element in the facade was unique in its shape and relations to neighbouring elements. ‘Only the nuts and bolts are standardised, everything else in the façade varies’, another project façade architect told me.

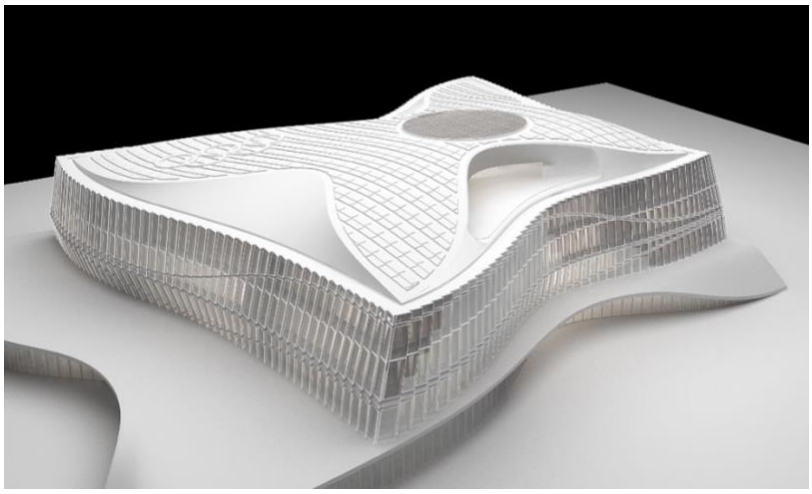

Fig 8.8 IOC façade model with the five freeform curves – top, bottom, middle and two waves – visible for two sides.

The team began to look for ways of formalising these relationships that would minimise their complexity: 'Everything was curved. In all directions. We had to find a limitation, first we tried single curved, and later we settled on plane glass panels.' Kenn explained. Due to the freeform lines of the five curves drawing the façade, its initial shape curved in both horizontal and vertical planes. While this works fine in a Rhino model, it becomes incredibly difficult and expensive to construct on a building using curved glass. The plane glass panels removed this obstacle, but the design of the façade meant that any iteration in placement of these panels could have unpredictable consequences for the overall surface, structural integrity of the facade, building aesthetics, and performance.

Data model

To understand and manage these relationships under tight deadlines, the 3XN team needed to develop a modelling platform that could tie the specialisation and expertise of design and façade detailing into an efficiently working whole. When I interviewed Søren, the 3XN project lead for the IOC, he explained why:

> The façade was so complex that we could not simply solve a single piece and be done with it. We could not manage the geometries. We could not manage the consequences of a change before actually doing the change and implementing it across the full building. We had to get [the change] all the way round in the building.

To get changes 'all the way round in the building', the digital design team established a data structure linking the façade model across Rhino and Revit software using Grasshopper, Dynamo, and bespoke scripts and code to create a two-way data link[34]. This data structure allowed the team to identify and link individual elements in the two modelling environments such as glass panels and columns for the facade. This enabled parallel design work in Rhino and detailing work in Revit thereby leveraging the affordances offered by the digital materiality of each software (see Ch. 5).

[34] See Chapter 5 for a detailed description of the 3XN and GXN modelling platform.

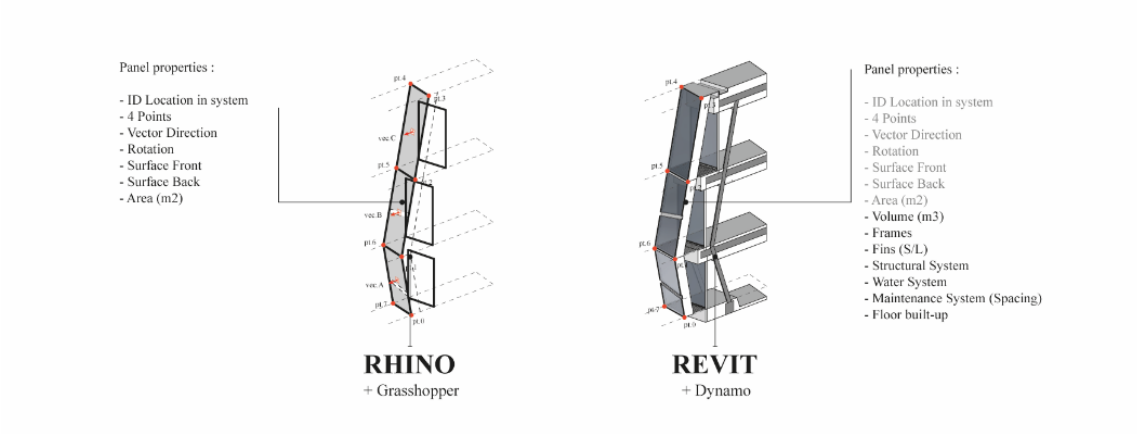

Fig. 8.9 Predefined data structure linking elements across modelling environments enables iterative integration of element data in Revit while maintaining geometric flexibility in Rhino.

As we got further into our paper for the Design Modelling Symposium and began unpacking the IOC facade in more detail, Kenn explained to me how the data connections were set up around a 3-dimensional building grid which allowed for locating each individual façade element. Within the grid, individual elements were assigned four corner points, a perpendicular vector describing its angle and orientation against the grid, and a unique id number (fig. 8.9). This established an explicit data structure for connecting individual elements across the Revit-Rhino modelling platform.

The data connection allowed for export of geometry and data from Rhino (where competition drawings and the first façade iteration were developed), which was then re-created in Revit. When I asked Kenn why this was important he lit up and explained how the link established continuous feedback between the software environments, connecting different resolutions of design and detailing; Rhino was used for large scale façade design and optimisation, while Revit was used for local detailing, documentation and classification of families such as load bearing columns and glass elements (fig. 8.10). Through this interaction between local construction detailing and overall design modelling, the IOC model integrated aesthetic concerns with technical solutions to problems posed and explored with a range of specialist collaborators during project development phases.

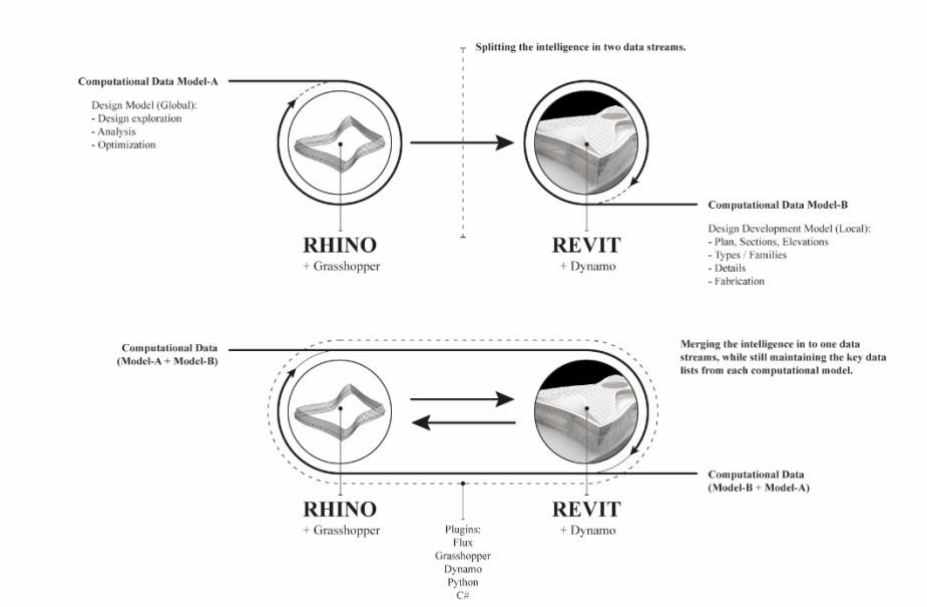

Fig. 8.10 Modelling platform establishing two-way data link between Rhino and Revit to keep building intelligence live (below) and able to inform local and global design development.

8.3 Olympic House III: Design Research

Kenn explained that feedback from façade engineers and structural engineers led to a focus on optimisation of façade elements and the introduction of a double skinned façade to ensure that the finished building could combine expressive design with high energy performance. A glass façade lets in more sunlight, necessitating more energy for cooling the building. Analysis from engineers had shown that energy demands for single skin façade clashed with the IOC's ambition to reach the highest possible energy performance. A double-skin façade introduces two façades (or skins) placed with spacing in between for ventilation and insulation, thereby ensuring better energy performance of the building.

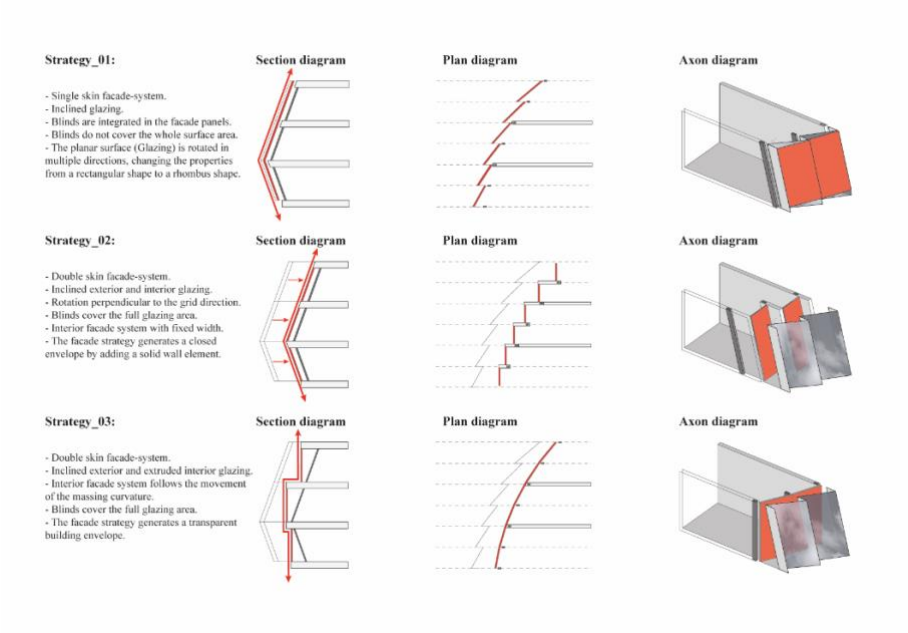

Fig. 8.11 Design research for geometric implications and optimization around introduction of double-skin façade..

On the IOC project, the double-skin introduced an interior and exterior glass façade (fig. 8.11), but their design presented problems. Once the engineers returned with structural details and these were "massaged into the model" as Kenn said, the angle of the load-bearing columns of the façade as well as the spacing between inner and outer skin varied greatly due to the dynamic form of the façade itself. Kenn explained:

> The problem was that the more acute the kink in the outer façade became the bigger the distance to the inner façade. At some points we nearly had a full Copenhagen apartment in between them. Suddenly we found that we had to have a dialogue between the ways we were manipulating design curves, fabrication methods, and simulation [of e.g. solar radiation and daylight] to understand how we could maintain the core of the project, the aesthetic keywords of movement, flexibility, sustainability. These were core values no matter what.

The double-skin façade placed high demands on the 3XN team and their structural and façade engineer collaborators. As each section of the façade was unique and all elements were parametrically connected, developing construction details required ongoing integration of a variety of parameters. As complexity grew, the model and data structure developed by the digital design section came to prove itself as an essential environment for design research and collaboration.

Integrating design language and structural detailing

For the Design Modelling Symposium, Kenn and I had decided we needed a few key examples of how this collaboration worked and was structured. As the paper progressed, Kenn elaborated on these examples while emphasising their highly collaborative nature. They illustrate how the modelling environment came to serve as a cognitive ecology as argued in Ch. 4 and 5. The collaboration they confirm, begin to show how social coordination is integral to the concept of digital materiality, which I will discuss further in Chapter 9.

Using the linked modelling environment and data structure, several 2D sections of the façade were exported to structural and façade engineers along with data about their relation to the wider model. These sections showed the two skins of the façade with the angle of loadbearing steel columns and distance between them. Based on this, the engineers developed basic construction principles for the façade. These principles initially focused on defining minimum and maximum angles for the loadbearing steel columns supporting façade and floors (fig. 8.12).

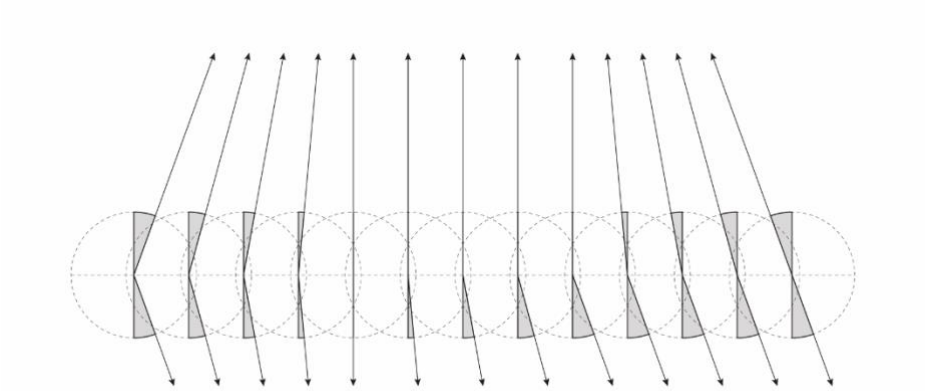

Fig. 8.12 Exploration of inclination and angles for load bearing columns of outer façade.

Kenn explained that if the angle of the loadbearing columns became too acute, the structure would either threaten collapse, or the column had to be widened to an unacceptable degree from a design perspective. The variable façade spacing between inner and outer skin also presented

problems. Too much and too little space would severely impact the performance of the façade in terms of light, energy, and ventilation.

Swiss regulation threw another unexpected curveball at the team. The facades had to comply with Swiss mandated minimum working requirements for cleaning contractors. While simple enough on paper, the introduction of another set of parameters to be integrated into the design heightened complexity and proved troublesome. Kenn explained:

> The core problem is, we have the angles and the spacing, now we need a cleaner in between. A Swiss cleaner. Making room for him means our façade must be pushed out. Well that leads to a gap in the top, so now I must push the bottom out to maintain the aesthetics, and all of a sudden, we are back at the full Copenhagen apartment in between.

To communicate this problem to the team of collaborators doing façade detailing, Kenn created an additional parametric script for computing and visualising 3D spacing between interior and exterior skin (fig. 8.13).

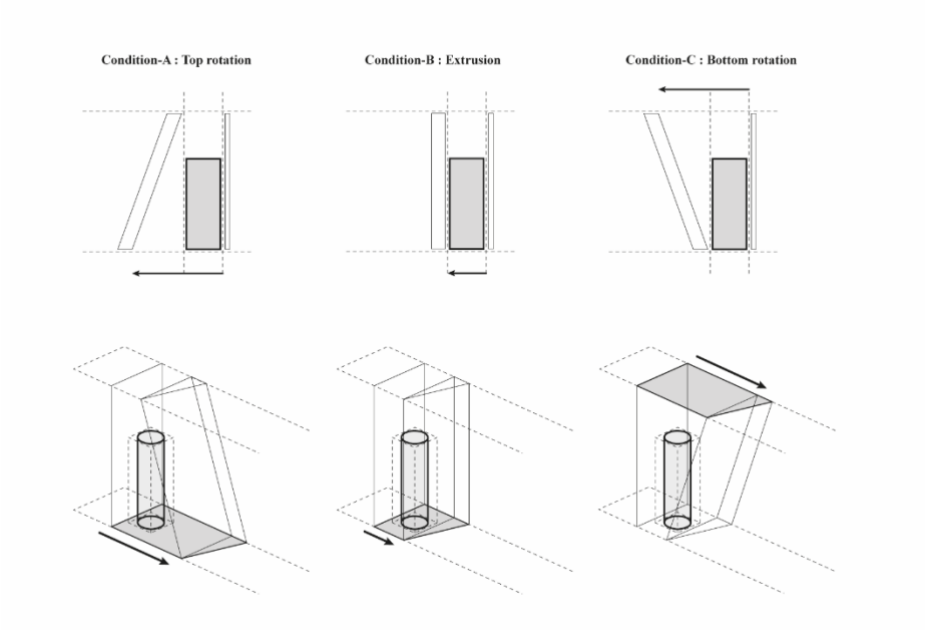

Fig. 8.13 ‘The Swiss cleaner.’ Computing 3D spacing between interior and exterior skin to meet minimum mandated working requirements.

Façade development lasted several months with continuous exchange and collaboration between 3XN, façade and structural engineers, the local architects keeping track of regulation, and the client. Kenn explained how, for each iteration, the design team used the modelling environment for comparative analysis across form, angle and spacing in the façade structure to ensure that all sections remained within the established structural parameters while also maintaining the overall dynamic design of the building (fig. 8.14).

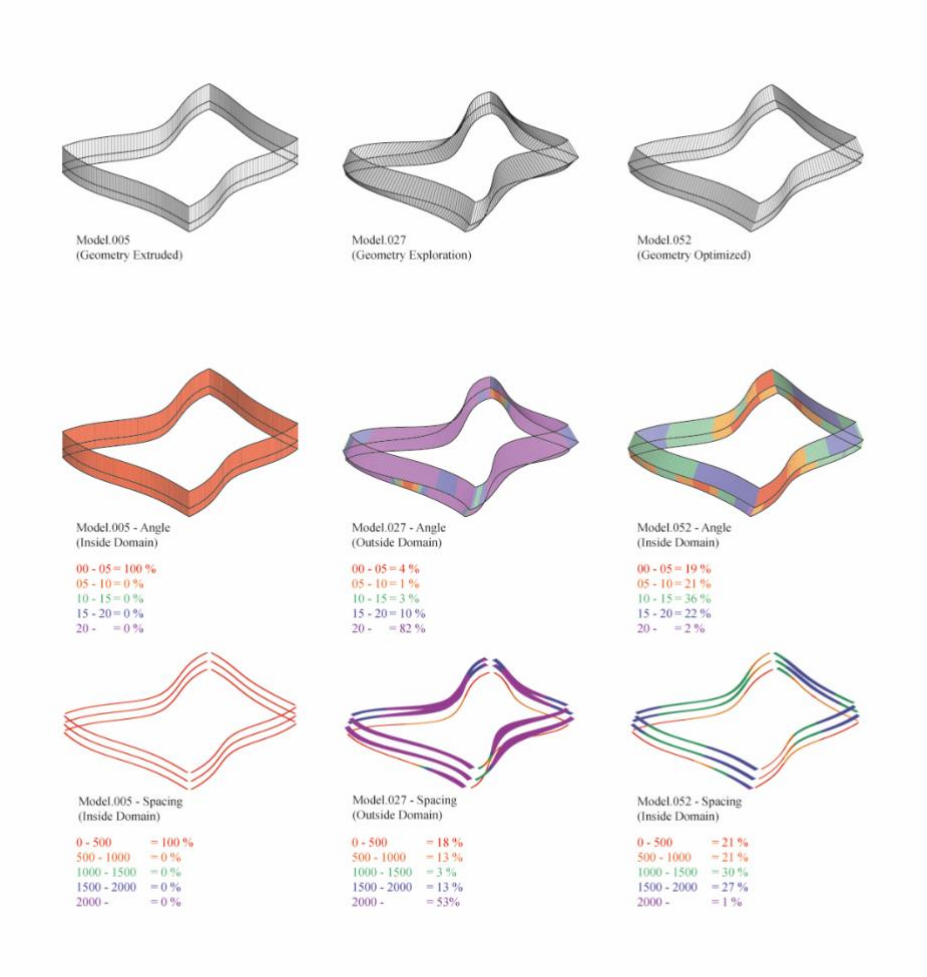

Fig. 8.14 Design research into form (top row), angle (middle) and spacing (bottom) for the IOC façade. Comparative analysis across these domains allowed the project team to evaluate structural performance and aesthetics to find the best design integration.

When I talked to 3XN projects leaders for IOC, they all emphasised that the modelling environment linking elements across Rhino and Revit served as an essential backbone for the

project. The data structure enabled quick analysis and exchange of building data during project development, they explained. This proved crucial for enabling fast exchanges in the wider team of collaborators, and for establishing a shared frame of reference as the project evolved and complexity grew. Collaborators could work on specific localised input, such as the structural integrity of façade elements, while 3XN architects managed the integration of these input data in keeping with the overall design intent of the project (see Ch. 5 for a discussion of how the 3XN and GXN modelling platform enable integration of multiple simultaneous practices inherent in design).

8.4 Project and dividual

The IOC competition allows us to restate and explore the problem opening this chapter: if situated participatory sense-making is the process through which collective meaning is created by design teams, how is the expertise of architects and collaborators meaningfully integrated across the full lifetime of a project? My answer builds upon discussions of dividual personhood in anthropology (Marriott 1976, Strathern 1988, Mosko 2010, Pina-Cabral 2017). Debates about dividuality are as multiple as the concept they seek to clarify, I do not propose a full coverage of these debates (see Lambek 2015, Schram 2015 for recent overviews) but will specify the concept as I apply it here.

My application of dividuality, begins with a quote from anthropologist McKim Marriott:

> To exist, dividual persons absorb heterogeneous material influences. They must also give out from themselves particles of their own *coded substances*, essences, residues, or other *active influences* that may then *reproduce in others something of the nature of the persons* in whom they have originated. (Marriott 1976:111, my emphasis)

Marriott's conceptualisation of 'dividuality' posits that personhood and agency are relational categories inseparable from exchanges with people around us. This relational perspective stands in contrast to western concepts of 'individuality' which sees personhood as distinctive and self-

contained. Marriott's (1976) analysis was based on ethnographic work in India during the 1950s. In it, the dividual person emerged as a composite of varying hierarchical connections to other people instantiated by *coded substances* exchanged between them. These substances, such as blood, food, and knowledge, came to reproduce the relational intricacies of Indian caste society.

Adopting these ideas, anthropologist Marilyn Strathern (1988:348) described how Melanesian tribes considered the person a composite of shifting relations with other people established through kinship, blood, gifts, food, magic and ceremonial exchanges. In Strathern's work, personhood emerges through social connections and persons become aggregate sites of the relationships that produced them. Persons are multiple in Strathern's analysis, this multiplicity is borne from and extends through material and ritual interactions with other people. Being multiple in this way, persons are also partible and able to exchange vital parts of themselves with others (ibid. 185).

In recent discussions of dividuality (Pina-Cabral 2017:64, Mosko 2010, Coupaye 2018), distinctions between dividual and individual personhood are blurred and the recognition that all personhood relies on degrees of dividuality is coming to the fore. In line with the distributed perspective of digital materiality which draws on material engagement theory (Malafouris 2013), cognitive ecology (Hutchins 2010, 2005), cultural theory (Douglas 1988, Rayner 1992) and participatory sense-making (De Jaegher and Di Paolo 2007), I see dividuality as a central fact of what it means to be a person amongst others. And I see digital materiality play a key role in this for the architects at 3XN and GXN.

Anthropologist Mark Mosko's (2010) analysis of Melanesian ethnography points to the need for a more dynamic concept of dividuality which encompasses western society and allows for social changes through time. To this end, Mosko calls for a clarification of:

> the relation between dividual and individual personhood in such a way as to enable exploitation of the *dynamic potentialities of partibility and elicitive exchange as change*, and which takes due account of *processes analogous to dividuality in introduced dimensions of presumably individualist Western sociality* (ibid 216, original emphasis).

I propose a modest answer to this call here by looking at how creative agency and mind is enabled through distributed exchanges of digital code between collaborators in 3XN projects. Creative agency becomes inextricably social in this perspective. Mosko's discussion underscores the transformative and situated nature of our dividual engagement with people and materials. The partibility of the dividual person, argues Mosko, means that she is a composite of prior social and material entanglements and that present entanglements indicate her potential for future action. Following Marriott (1976), Strathern (1988) and Mosko (2010), I consider creative agency as inherently relational, composite, and tied to specific contexts, people, technics, and materials. From the anthropological discussions of dividuality, I draw two specific elements for the analysis of creative agency and collective mind in the studio of 3XN and GXN:

> (1) *materiality*, following Mariott (1976), I consider that people's creative agency is made and remade through circulation of various coded substances, including technics, code and data[35].
>
> (2) *agency*, following Mosko (2010), I therefore also consider the dividual a potential agent of change, whose past and present entanglements at any one time defines this potentiality.

These are analytical elements. They do not necessarily correspond directly to the way architects at 3XN and GXN describe themselves and their work, though it is striking how notions of coded substances, creative exchange, and historicity are part of the answers architects provide to questions about their own creative potential. While these elements do not touch upon the full richness of the concept of dividuality, an analysis of digital materiality and modelling practice can go some way in identifying processes analogous to dividuality in a western field of practice.

Returning to the studio of 3XN and GXN, the dividual perspective on personhood, creative agency, and mind will allow us to recognise how architects absorb and transmit knowledge,

[35] There is a precedent to this perspective: the concept of dividuality was picked up by Deleuze (from Strathern) in Postscript on the Societies of Control (1992) where it was used to describe the partial nature of people as data entities collecting and sharing data about themselves enabling new bureaucratic forms of control.

expertise, and materials throughout a project's lifetime. In this way, the concept of dividuality can expand prior discussions in this thesis by analysing how architects become entangled with an array of digital and coded materials (Ch. 4) and larger modelling environments (Ch. 5) through dynamic transactions that rely on manipulating embodied knowledge (Ch. 6), to create possibilities for collaboration, which rests on institutionalised forms of participatory sense-making (Ch. 7).

Project and dividual 1: materiality – coded substances

Discussions of dividuality argue that creative agency is constituted through entanglements with all sorts of coded substances, which, following Marriott (1976:111) come to reproduce in others something of the nature of the persons in whom they have originated.

In the Studio of 3XN and GXN, some of these coded substances are quite literally code. They are present in the digital scripts and models that come to form part of digital materiality and cognitive ecologies for architecture projects (see Ch. 4-5). Returning to competition design and project development of the IOC Headquarters can show how these coded substances form meaningful connections between architects and their collaborators across a project's lifetime. This will enable us to see how architects enact social design situations through the creation and circulation of scripts and models, and how architects themselves come to be conduits for extending the reach of digitally anchored cognitive ecologies at 3XN and GXN.

Recall the IOC staircase. It utilised the logo of the five Olympic rings seen through 3XN's design concept for the competition. And it has come to instantiate this relationship in a highly visible way within the central atrium of the building. The idea for the IOC staircase originated with an intern, but the stairs were subsequently developed in the 3XN team across both Competition and Project Development departments.

In its early incarnation in the 3XN competition submission, the staircase was drawn in 3D using Rhino and was subsequently rendered in views for the competition submission. It was not created as a parametric model at this stage. The initial concept was represented as an aggregation of geometric forms with no explicit coded relations between parts.

The shift from Competition to Project Development entailed a shift from concept design towards buildable geometry. As it came time to develop construction documentation for the stairs, the 3XN team discussed whether the initial drawings could be built to resemble the views and renders from competition hand-ins. Laura, who was responsible for the IOC staircase during project development, created a parametric model, which could formalise the design. In our interview, she recalled creating the script for the staircase:

> The only way I could really imagine doing this was building it with a script. So, you look at what it is and say, ok this is the logic behind how someone conceived it, and then build that logic into the script. You know, this is the person's idea, now I will parametrise it so we can say ok what if the circles get bigger, what if the stair needs to be wider, all these kinds of things.

By developing a parametric script for the staircase, Laura formalised the conceptual design in coded mathematical relationships between parts within a parametric model. She appropriated digital materials from the competition team to reproduce elements of thinking from the person who had the initial idea, and the team who subsequently modelled and rendered the staircase. Parts of other people's ideas and logic – 'active influences, residues or essences' (McKim 1976:111) – came to be part of her own creative agency in the project. This formalisation of ideas, logic and relations in the coded substance of the parametric script enabled herself and 3XN team to collectively work on the staircase as the project developed. Laura elaborated:

> I did not design the idea of the IOC stair … so one thing was to build the script to be able to analyse and adjust its elements. One of the things that we did with the IOC stair was evaluate its form and function and how we could optimise those things … There were big picture kind of adjustments, we were looking at renders, we were looking at diagrams or sections and then finding out what issues still remained and then trying out things through the script.

The technically mediated exchange of ideas through digital scripts and models in the IOC project helped facilitate collaborative relationships that allowed different people to develop shared concepts over time. Laura pointed out that she became a node in this relationship, as she alone had carried out the work of appropriating and codifying the logic of the initial idea in the script:

> I think it is a limitation of that process because nobody else could really work on that script other than me. I am sure an experienced scripter could get in there and figure out what was going on and take it over to keep working, but it was very difficult for [3XN project lead], for example, to go in and make a quick change, I needed to make the changes

Her creative agency in the IOC project was tied to her mediated relationships to a variety of people, both current project leaders and competition architects no longer working on the project. These relationships were mediated through exchange of coded substances, the digital script and model for the IOC stairs. While we were talking about creating the parametric model, Laura explained why collective agency around the staircase became intimately linked to her work of appropriating and re-creating the underlying mathematical logic of the stairs: ‘everyone has their own signature [when scripting], just like you have a different way of writing than I do and it reads differently.’

These scripting ‘signatures’ are at one and the same time borne from the architectural projects they were developed through and highly personal for individual architects (see p. 174). This can make parametric scripts difficult to understand for architects who have not been part of their creation. Therefore, when taking over a project or idea, as Laura had taken over the stairs, the first task will often be to de-construct the project or script to understand its inherent logic, and then build it anew.

At 3XN, scripts are created and re-created by designers when projects move across phases or departments, yielding a bit of its underlying logic into these new situations. This seeds new and creative work through re-creation and formalisation of scripts in the larger context of the projects

they feed into and draw their impetus from. In this sense, data, code, models, and software become part of the dividual designer. I argue that digital materials play their part as conduits and anchors in the shifting situations of collaboration to the extent that we might compare models and scripts to Marriott's 'coded substances,' which dividuals absorb and transmit in their transactions with others.

It is, however, not simply the exchange of scripts and models that enable creative agency and collaboration in projects at 3XN and GXN, but the ongoing work of architects like Laura, and their continuing social interactions with others. From Strathern (1988:13) we have the notion that people's creative agency emerges from social connections and the exchange of coded substances, that people become essential nodes for bringing together these relationships. In this sense, Laura became a collaborative node for a part of the IOC project. She connected architects, interns and project leaders across early concept design and ongoing project development through her work with the script for the IOC stairs. The dividual nature of these relationships, her absorption and exchange of other people's ideas and her own creative work reproducing and modulating these ideas via code, where intimately tied to her role as a conduit for creative agency in the larger project team.

Project and dividual 2: agency – shifting entanglements during project lifetime

From Kenn's account of the IOC project, we saw that creating the parametric façade model relied on a similar decomposition of a design into basic parametric logic and then re-creation of the design through a parametric model. Developing the model allowed Kenn to absorb freeform geometry from the Competition team and formalise it as a parameterised data, which could be selectively transmitted to a wider group of collaborators. Kenn explained how data structure and exchanges were at the core of these wider collaborative relationships in the project:

> The Rhino [geometry] model really does not exist. All that exists as input [to Rhino] for this building are the 20 curves and a grid. Everything else is numbers and vectors built up around the five times four curves. This is where geometry versus data suddenly becomes interesting. The

> [file] size is nothing. It is nada. Because it only has to contain those things – and then it becomes represented via Grasshopper, Python, all this code-based flair.

The core of the linked modelling environment for the IOC project were the 20 curves needed to describe the movements of the façade, and a grid-based data structure. This data structure identified all elements in the model and enabled quick exchange with project partners which was key for integrating their expertise into a shared understanding of the interdependencies of the façade.

Transmitting and absorbing ideas and expertise from collaborators was essential during project development. The data structure enabled sending and receiving vast quantities of coded substances: sections, details, and data packages between the 3XN team and collaborators such as façade and structural engineers. In this way, the IOC façade model established a link for technical and aesthetic participatory sense-making across the project's lifetime. In line with my discussion of participatory sense-making (Ch. 7), the very structure of these interactions across digital materiality and collaborative institutions became part of the sense-making process. The linked modelling platform enabled the creation of shifting relationships between geometry, data, sections, and expertise of architects, façade engineers, and structural engineers, while leveraging the different possibilities of the Rhino and Revit software (fig 8.15).

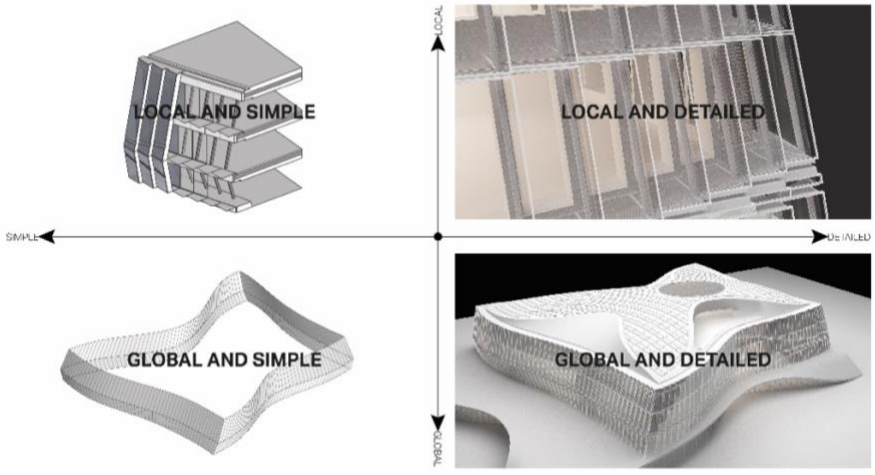

Fig. 8.15 Linking elements in the IOC model across Revit and Rhino allowed the team to work at different resolutions and problems at once.

The digital materiality of Rhino and Revit enabled ‘change through elicitive exchange’ as it were (Mosko 2010:216). The modelling platform linking Rhino and Revit allowed the exchange and manipulation of geometry as data and data as geometry, enabling collaborative exploration of how different structural problems and solutions would affect the overall design expression. The architects could send and receive visuals and data to several different collaborators at once. They could recast structural optimisation problems from Revit into visually coded geometry in Rhino, which could be compared and analysed by the design team who thereby maintained control of form and design expression throughout the project.

The efficacy of the IOC model and workflow lay in the possibilities it gave the 3XN team and their collaborators to selectively zoom in on, mix and process specific aspects of local and global design development while ignoring others (fig. 8.14, see also Ch. 5). The rigidity of the data structure underlying the modelling environment and simultaneous fluidity inherent in the linked software meant that design collaboration on the project could move between two poles: at one end was aesthetic interpretation with rich scope for dynamic iteration, at the other, the data structure serving as notation system in which the structural options were comprehensively coded.

This permitted research into the complex façade at a human meaningful scale, allowing the 3XN team to continuously model input of collaborators and circulate these in the project group to find the best fit between structural performance and design aesthetics. The modelling environment with its different possibilities for representation of the same underlying data facilitated the integration of different people and expertise across the IOC project’s lifetime.

Conclusion to chapter

The argument of this chapter is that architects draw ideas, concepts, expertise, code, and technics into their dividual selves via ongoing exchanges with digital materiality. Perceiving architects as dividuals allow us to see how they enact creative agency through ongoing exchanges with people at different stages in projects to create meaningful collaborative relationships. The architect's entanglements at any one time forms her potential for thought and action. Her dividuality allows her to act in conjunction with others to enact meaningful relationships. Through digital models which both stabilise geometry as data and permit its manipulation in shifting situations, this agency becomes distributed amongst a wider circle of collaborators.

The focus on projects adds a longer temporal perspective to discussions of participatory sense-making explored in the previous chapter. It introduces dependencies and continuity between temporal scales and situations: people do not enter design situations as blank slates with clearly defined individualised goals, but as dividuals bringing a history of past and present entanglements that shape their expectations, experiences, and opportunities for thought and action (see also Rietveld and Brouwers 2016:200).

Mosko describes this well when he says of the dividual that: 'Every action – or transaction – is in this way both conventional and innovative.' (Mosko 2010:218) In the studio of 3XN and GXN we have seen that situated practices are conventional because they re-create prior ideas and practices, and innovative because the partibility of architect and situation offer new possibilities for re-making the self-same ideas and practices in the process.

In this way, technics serve as a conduit for establishing a rich relationship between designers, their models, and the shifting teams, projects and studios they engage with. Formalising geometry through mathematical logic and creating a conduit for experimentation within the team, parametric models and scripts become akin to the coded substances flowing between persons to enable creative

agency and social mind. In line with the distributed perspective of Material Engagement Theory, cognitive ecology, cultural theory and participatory sense-making, I have argued that dividuality is a central fact of what it means to be an architect at 3XN and GXN. As Douglas and others remind us, people are participants in a fluctuating world where meaning and stability can only be achieved through collective work. Discussions of dividuality allows us to see how digital materiality come to be part and parcel of this collective work at the design studio.

Agency and mind become social in this view. They emerge in exchanges between people and materials in specific organisational and technical environments. As we have seen in this chapter, there are clear organisational aspects to this. As people move through different social situations the dividual person becomes saturated in collective meaning, at once shaped by and shaping collective processes in all their richness. This links my conception of dividuality to more dynamic strands of cultural theory and their analysis of how different social organisations come to shape people's capacity for thought and action (see Rayner 1992). And this link is what I will explore in the next and final chapter.

Chapter 9: Studio

A project like the IOC Headquarters shows the variety of problems faced by architects at 3XN and GXN. The project shows how architects at the studio need to integrate different forms of practice and expertise during years of creative problem solving: open-ended ideation when developing competition concepts; systematic problem-solving during project development; and close design research with collaborators to resolve more complex problems.

To understand how these different practices can result in coherent architecture after years of work, I maintain that we cannot start from the individual architect but must begin from the collaborative nature of design work at 3XN and GXN. This argument has been guided by the work of Mary Douglas, specifically her focus on how people come together to pin down and stabilise meaning trough collective ways of working, thinking, and engaging with the materials of the world. In this chapter, I will focus on the relationships between digital materiality, collaborative practice and social mind in the studio.

Taking up the mantle from Douglas, anthropologist Steve Rayner (1992) has made the case for a shift in social science from a focus on individuals to a focus on connections between them as the salient explanatory point. Considering the chapters in this thesis, I would argue that this focus should extend beyond relations between people to relations between people, materials, and technics, which all form part of a rich and meaningful context for creative practice.

How to balance these relationships throughout a project's lifetime is a core challenge for the architects at 3XN and GXN. Meeting this challenge requires purposeful alignment of digital models and institutionalised patterns of collaboration in the studio. In Section II, I showed that there is a flexibility to digital modelling in the studio. This flexibility is created from the combination of several software with variable digital materiality into one connected platform that can integrate the many moving parts of a design practice and projects. This flexibility finds a parallel in the social

organisation of the studio where different departments and practices allow architects to engage with projects in diverse ways (see also Ch. 5).

Digital materiality posits that there is an interdependence between technical and organisational relationships which enables greater flexibility for the architects. In Chapter 5, I argued that the efficacy of the 3XN and GXN modelling platform lies in the way it lets architects integrate, hide and bring forth specific relationships in the parametric models they create. Here I will argue that manipulating relationships in the model also allows architects to shift contexts for collaborative practice and social extension of mind. The differences in digital materiality in the software making up the modelling platform support different practices during the phases of a project. These practices are embedded within larger contexts of social organisation in the studio. Together, the social and technical coordination of collective work in the studio enable a balancing of stability and flexibility which is needed to meet the challenges posed by architecture projects. By focusing on stability and flexibility, I seek to develop the discussion of sociality of mind further by showing how shared dispositions of varied scope and durability develop, are maintained, and change through overlapping technical and social organisations inherent in digital materiality. I do so by revisiting the IOC project to analyse how social organisation and software combine for design teams.

9.1. Towards a dynamic cultural theory

Mary Douglas posed the question of mind explicitly in social terms in her 1986 book *How Institutions Think.* Here she argued that social institutions carry more cognitive load for people than many contemporary social scientists allowed for. Douglas' work on relationships between social organisation, behaviour and thought have been developed under the banner of cultural theory. There are several approaches to cultural theory (e.g. Douglas 1988, Thompson et al. 1999, Verweij et al.

2006, Rayner 1986, 1992, Rayner and Malone 2001), here I will outline my own conception, which follows the work of Rayner. This work outlines key aspects of a dynamic version of the theory, which will enable the analysis of digital creativity and social mind at 3XN and GXN.

The Mobility Hypothesis

Rayner has developed a dynamic approach to cultural theory through analyses of collective sense-making across professional and technical environments (Rayner 1984, Rayner 1991, Rayner 1992, Healey and Rayner 2008, Patel and Rayner 2012). These analyses share a core assumption with the work of Douglas, namely that people perceive and manage day-to-day practice according to principles inherent in patterns of social organisation. Rayner pushes the theory of how people come to create, maintain, or upend, social meaning into a more dynamic perspective than originally proposed by Douglas. He argues for the existence of plural rationalities within organisations, and a framework that takes into account how people switch between meaningful practices dependent on the social contexts they find themselves in (Rayner 1986, 1992, Rayner and Malone 2001).

In a 1992 article on cultural theory and risk analysis, Rayner outlines the core tenets of this perspective. He argues that cultural theory approaches risk perception from the assumption that people are participating as creators of meaning rather than passive receivers of information. Rather than view people as isolated information processing individuals, they become active: 'groping with […] the world in the search for information.' (Rayner 1992:85) In light of the discussions in this thesis, we should say that this search for meaning entails active, or enactive, creation of meaning. As Rayner takes care to argue, this is a collective activity: 'cultural theory is fundamentally a social theory concerned first with *relationships* amongst human beings and second with societal relations with nature.' (ibid. 86, my emphasis) This focus on relationships as the salient point of analysis is key to the dynamic perspective he develops. It does away with critiques of essentialisation and

determinism, which has been levelled against cultural theory by detractors arguing that the theory deals mainly with stable personality types that cannot account for plurality and change. Rayner goes against this criticism with what he calls *the mobility hypothesis*: 'individuals may flit like butterflies from context to context, changing the nature of their arguments as they do so.' (ibid. 107). He is concerned here with how organisations emphasise or hide certain risks, by managing what people can say and still expect to be taken seriously. This does not, however, mean that context and sense-making are mainly discursive in Rayner's dynamic view. In the same article he also emphasises how the material world, what he calls *natural feedback*, comes to inform knowledge processes with or against cultural aspects:

> The combination of natural feedback with cultural constraints on the organisation of information forms a total knowledge system, parts of which (to use the jargon of systems analysis) may be overdetermined by either cultural or natural constraints at different times and places. However, both types of constraints are always present in the knowledge process and profoundly shape our most fundamental ordering concepts, such as space and time. (ibid. 99)

As we have seen throughout this thesis, meaningful relationships are forged through materials and technics as much as discourse. Digital materiality's attention to the mixing of technical, material, and collective worlds marks a productive intersection between dynamic cultural theory, Material Engagement Theory (Malafouris 2013), cognitive ecology (Hutchins 2010), and participatory sense-making (De Jeagher and Di Paolo 2007). As discussions of material agency in Chapter 4 and dividuality in Chapter 8 showed, creative agency is partial and contextual, constituted through shifting social and material relationships. In the design studio, these relationships are made and remade as architects engage with a variety of coded substances, such as data, scripts, and models, which take on meaning through circulation within shifting institutional contexts. Following examples in this thesis we can say that a dynamic version of cultural theory must be inherently relational and enactive. It should presume active involvement of persons and

their wider social and material contexts and emphasise an analytical focus on the relationships that are made and remade through situated interactions between people and their world.

This perspective is grounded in a dynamic reading of cultural theory's 'grid' and 'group' dimensions. Originally developed by Douglas in *Natural Symbols* (2003[1970]), grid and group describe patterns of relationship between people. The 'group' dimension describes the extent to which people's thoughts and actions are restricted by their commitment to larger social units such as company, political party, or religious group. Group strength is high when people are deeply committed to the group, low when they are left to their own devices. The 'grid' dimension describes the extent to which people's thoughts and actions are determined by role differentiation. High grid entails a high degree of specialisation and segregation on grounds of hierarchy, age, lineage, and so on; low grid exists when such distinctions are weak. (Patel and Rayner 2012) Together, the two social dimensions form a fourfold describing patterns of social organisation, which give rise to specific tendencies in social interactions. This fourfold is at the core of cultural theory.

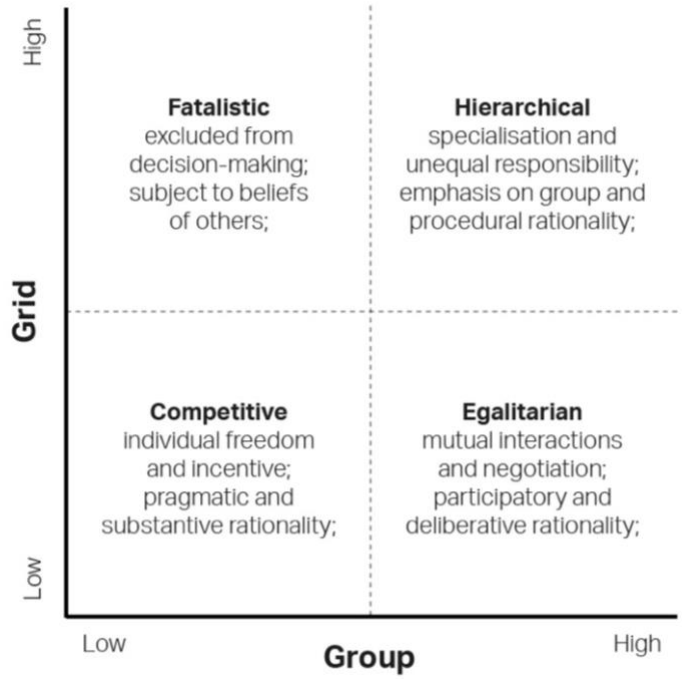

Fig. 9.1. Dynamic grid/group diagram, the different dimensions are on a continuum and describe context specific interactions rather than separate and fixed identities

In the dynamic version of cultural theory, I seek to develop here, the fourfold describe patterns of interactions and thought that change dynamically along the dimensions of the model (fig 9.1). Following Rayner this model describes a plurality of interactional patterns and social relationships, which can exist at once within an organisation; this allows people to dynamically shift interactional patterns dependent on institutional contexts (Rayner 1992:107, Patel and Rayner 2012:127, Rayner and Malone 2001:192).

Relationships: cultural theory, Material Engagement Theory, participatory sense-making

The dynamic version of cultural theory grounded in Rayner's work highlights a fluid mode of social analysis with a focus on how people make and remake relationships across the grid and group social dimensions. This analytical framework is close to the situated and enactive perspective of digital materiality and its grounding in Material Engagement Theory (Malafouris 2013), cognitive ecology (Hutchins 2010), and participatory-sense-making (De Jaeger and Di Paolo 2007).

As Malafouris (2013:100) points out, a key element of enactive theories of mind is the implicit creation of correspondences between domains of experience that blend bodily, material and symbolic inputs. In these frameworks, the difference that makes a difference is neither isolated information, representations, identities, or desires, nor objects, tools or materials, rather it is how these are coupled in ways that reorganise the cognitive system to enable new possibilities for thought and action (Malafouris 2013:81, see also Hutchins 2010:710 Bateson 1987[1972]:256). In Section II, we saw how the configuration and digital materiality of design software and their coupling in the digital modelling platform at 3XN and GXN came to shape possibilities for design practice and creative extension of mind. Dynamic cultural theory can help draw out the implicit social assumptions and rules making these interactions meaningful in the studio context.

Philosophers Hanne De Jaegher, Ezequiel Di Paolo, and Shaun Gallagher (2010) have pointed to how specific interactional dynamics can become constitutive of social mind. Gallagher's (2013) concept of social mind reaches beyond the immediate affordances of situated interactions between people to also rely on institutionalised structures, norms and practices. Gallagher suggests that participatory sense-making come to rely on the way we grasp each other's actions in terms of their appropriateness in specific situations. In Chapter 7, I argued that this appropriateness is tied to institutionalised patterns of behaviour and thought in the design studio.

The work of Rayner and Douglas encourage us to bridge dichotomies between action and context (mind and environment, individual and society, etc.) to ask how they come to co-produce each other through situated practice. I argue that the shifting practices of design intimately link objects and processes under creation with the collaborative process of creation itself, and that social mind and digital material engagement is vital for design practice at 3XN and GXN. This argument sees patterns of interaction as socially shared and materially anchored cognitive ecologies that fundamentally change people's possibilities for thought and action in the design studio. It explains how collaborative practice in the studio of 3XN and GXN are supported by both organisation and technics, and how these practices can take on meaning of their own through a rich web of institutional patterns and digital materiality.

9.2 Patterns of interaction

The argument I seek to advance in this Section of the thesis is that there is a mutually constitutive relationship between digital materiality and patterns of collaboration and mind in the design studio, and that they influence each other across scales of collaborative practice, whether in teams, projects, or at the studio as a whole. Like any pattern, patterns of collaboration and mind are dependent on

contexts for their expression (Bateson 1987[1972]). From Douglas, Rayner, we know that people are active participants in the creation of meaning from the flux of events that surround them. Suchman argues that this type of situated action is: 'reflexively constitutive of the world's significance, which in turn gives behaviour its sense.' (Suchman 2006:15) In light of the enactive perspective advanced here, we can say that situated action brings together action and context as they both become part of the fabric of the unfolding situation.

Interaction, rationality, practice

So what exactly is the content of these patterns of collective practice? Rayner describe collective institutions that emerge as we enact meaningful worlds from the rich contexts around us. Through this engagement, relatively stable patterns of collective behaviour emerge. These patterns co-produce shifting forms of *interaction* as well as *rationalities* and *practices* that are rendered meaningful by these rationalities (Rayner 1986, 1991, Rayner and Malone 2001, Thompson and Rayner 1998, Thompson 2008, Douglas 1986, Douglas, M. and Isherwood, B. (1996) [1979]). In line with the dynamic perspective on cultural theory, institutionalised patterns emerge as people shift strategies in the grid-group fourfold. They do not become static or deterministic but give rise to collective possibilities for meaningful thought and action within specific contexts. These patterns of meaning have a fractal quality and are evident at all scale levels from shared beliefs about society and nature, through high level patterns of organising, ways of reasoning, and all the way down to minute situated practices and interactions (Verweij et al. 2006:24).

Following the grid-group fourfold of cultural theory, we can identify four types of interactional patterns, which come with distinct ways of organising, reasoning, and collaborating (fig. 9.1, see also Rayner 1991, Rayner and Malone 2001, Thompson and Rayner 1998, Patel and Rayner 2012). These patterns rely on distinct organisational forms, rationalities and expectations about the world,

which give rise to meaningful collaborative practices. The following is adapted from Patel and Rayner (2012:126), and Rayner and Malone (2001:193):

Competitive interactions (low group / low grid)

Low group strength means that people have a high degree of individual freedom and mobility; low grid strength means that people do not adhere to hierarchies. This gives rise to competitive patterns of interaction. Pragmatic, substantive and competitive rationality guide decision-making, and practices focus less on status or procedure, more on skills, incentives, and a successful end-result.

Hierarchical interactions (high group / high grid)

High group strength means that people share strong mutual bonds and accountability; high grid strength means that people have specialised roles and unequal status. This gives rise to hierarchical patterns of interaction. Procedural and hierarchical rationality guide decision-making, and practices rely on clear definition of responsibilities and processes.

Egalitarian interactions (high group / low grid)

High group strength means that people give considerable weight to mutual interactions; low grid means that their relationships are open to negotiation. This gives rise to egalitarian patterns of interaction. Participatory and deliberative rationality guide decision-making, and practices focus on creation of consensus.

Fatalistic interactions (low group / high grid)

High grid and low group strength means that people are excluded from decision-making and yet are maintained in hierarchical relationships to their group with little way of contesting decisions

imposed on them. This gives rise to fatalistic patterns of interaction and rationality as people do not perceive themselves to be in control of what happens to them.

Below I will discuss the first three interactional patterns as they relate to institutionalised organisation of digital modelling and social mind at 3XN and GXN[36]. The patterns of interaction across the scales of teams, projects, and studio not only create meaning; the process of creating meaning gives rise to institutionalised ways of organising and reasoning which shape collaborative practice at the studio. And so on, in a recursive process, where the tendencies of different patterns influence, strengthen or weaken each other. As we will see in the analysis of modelling practice and social mind on the IOC project, different patterns of rationality and practice co-exist and interact throughout the studio, just as dividuals co-exist and interact via dynamic exchanges of code, scripts, and models during a project's lifetime (Ch. 8).

9.3 Patterns of interaction at 3XN Architects and GXN Innovation

In Section II, I argued that the modelling platform at 3XN and GXN anchors cognitive ecologies (Hutchins 2010) that enable architects and teams to handle complexity at a human meaningful scale. The section explored digital materiality and technical dependencies in these cognitive ecologies to show how they came to shape digital design and modelling. Section III explores collaborative aspects of digital materiality as it informs situated participatory sense-making in teams, dividual exchanges of coded substances in projects, and interactional patterns in the wider studio.

[36] While more fatalistically tinged patterns might also exist in the 3XN and GXN studio, I did not come across these in any substantial way in my observations and interviews.

In the remainder of this chapter I will pull the two strands of technics and collaboration together to expand the analysis of the ways in which digital materiality come to influence modelling practice and social mind at the 3XN and GXN studio. In light of the empirical and theoretical discussions so far, we should expect to find divergent patterns of modelling practices and social mind in the studio of 3XN and GXN that nonetheless correspond to the mixing of grid and group dimensions in the fourfold. And in light of discussions in Section II of digital materiality, material engagement and skilled intentionality, we should also expect these patterns of practice and mind to bring into correspondence the affordances of specific ways of organising, teams, technics, software, and models in the studio.

Competitive patterns of interaction (low group / low grid)

Teams at 3XN and GXN can engage in competitive patterns of interaction. Examples of this can be seen when architects use Rhino and Grasshopper 3D modelers to do concept design, form finding and design research in early competition phases.

Patterns of interaction

In Chapter 7, Jesper, the 3XN Studio Director and an experienced competition project lead, explained that early competition work was driven by the need for finding strong architectural concepts to organise ideation and collective sense-making on projects. This need is accentuated by the short time frames of most competitions and the wealth of other work, such as façade design, floorplans and detailing, which is influenced by the concept. From the IOC project in Chapter 8, we saw how competition concepts at 3XN seek to marry form, function and storytelling to enable shared creation of meaning while ordering the many inputs required of competition teams. Jesper explained how this approach is organised at the studio:

> We encourage people to work in Rhino to ensure that we all work within the same universe … A lot of idea generation happens through a sort of automatic sketching. For the first pitch we might have 100 different suggestions. Of course you cannot create any volume for a hotel room or a concert hall, but besides these differences in programme we shoot in all sorts of directions. It is fairly free in that first period, and it involves different people.

According to Jesper, there is a general recognition in the Competition department that ideas and concepts can come from anyone working in the teams there – whether you are a principal, project lead, or intern is not important, the key thing is the idea itself. This analysis was echoed by Laura in Chapter 8, who explained how the early idea and concept of the IOC staircase was created by an intern before being further developed by the 3XN team.

By integrating input from individual architects with little concern for hierarchy, competition teams seek to maximise the number of ideas produced, and the speed with which they are evaluated, to quickly run though as many as possible and hopefully find the concept that sticks. Sean, a young competition architect, who discussed digital design research in Chapter 6, also talked about this individualised approach to idea-generation: 'If you have an input on a project, you do it yourself, and you test it, and then you have the other people evaluate.'

Sean explained how competition teams sat together in small clusters to enable informal screen based sharing of information. I noticed myself on assisting with competition input from GXN how competition architects will work on their assigned part of the competition, volume studies, façade studies, floorplates – while asking questions, leaning over and showing each other details on their screens. This shift between focused creative work and collective evaluation is incentivised by the possibility of informing design of the final project. Enlai, an experienced architect who led the GXN design team on the Circularity Lab in Chapter 7, also discussed this:

> In the part where you are creating options, then it is extremely helpful – and I think it is beneficial for everybody on the team – to be able to design for personal investment … de-hierarchising the whole situation to allow certain concepts to bubble to the surface.

The evaluation of ideas within competition teams is organic and pragmatic. While project leads will set out time-tables with overall milestones to organise competition work, day-to-day discussions in the team often happens on an ad-hoc basis. Sean explained this process via the competition he was working on as we did our interview:

> So [another competition architect] has been honing in on some of the floor areas, and looking at precedents from previous work that the office has done. It just happened one of the partners walked past, just doublechecking on how he was doing, and I was quite curious because as part of my sketching I was wondering about how they were going to make the auditorium. And so I went over. I just wanted to quickly get some numbers but, you know, talk started going into something else and then we saw some new fresh models from previous sketches and then the discussion turned to that, what they would do for the site and what they would do for the design, and so – yeah, everyone else from the team started coming over to have a look.

The close proximity of people within the competition department and open-plan office of 3XN and GXN support these impromptu sessions. Project leaders responsible for competition teams, the Creative Director and the Head of Design all sit with the competition department. On occasions where I helped GXN develop input for competitions, our teams would be just ten meters away from the action but could feel left out from the quick turn-over of ideas and decisions happening day-to-day. It became tricky to develop input that fit with the evolving context of the project as the social interactions, we were missing, quite literally become part of the creative process. Dora, another competition architect, started our interview by telling me how different the team-based working relationship in 3XN's competition department was when compared to her former job at a renowned international architecture studio:

> Here we work in small teams and we keep the team in the same place and seating position, so we can talk together. If something sparks up, you open a conversation with the people that sit right next to you, working on the project with you. You can have a small brainstorming session every time you want, which I find really helpful. When you are looking at [scripts] for too long, you become so drowned in it that you cannot think, and then this person will tell you, 'how about that,' and you suddenly realise 'oh you've solved the problem that I have been thinking about for three hours in one second! That was really cool!'

While the competition department was less hierarchical than at other internationally renowned offices (Dora's experience was echoed by several international architects, I spoke to in their first weeks at the 3XN studio), there remains a tension between collaborative and competitive practices in the form of a certain zealousness around ideas. Sean explained:

> You always want to work on it, you can always spend more time on something. You have a deadline, you work right up to the deadline, always right up to the deadline. There is always more you can do, there is always more that you want to work on.

But here the close placement of teams and ad-hoc and substantive nature of decision-making helps bring the architects, and their ideas, together. Sean elaborated:

> [if a partner] sees something on someone's screen and they start talking, suddenly we are all up and talking, and we are sharing everything we have worked on. Which I think is also quite nice. It is definitely not a bad thing. If you were to have a set deadline, if they were going to say 'Friday evening we are going to sit down and share what you've got,' this would put a lot more pressure on to you, and I guess this would lead to more secrecy.

Modelling platform

Competition architects in the 3XN and GXN studio rely almost exclusively on Rhino and Grasshopper for their work (along with visualisation software for renders). The digital materiality and configuration of Rhino and Grasshopper supports the quick-fire sketching and pragmatic design research described by Jesper, Enlai, Sean, and Dora. In Chapter 4 and 5, we saw how NURBS representation of geometry allowed for quick creation and manipulation of shapes and volumes using the Rhino modelling interface. Creating a volume is done with just a few drags of a mouse using the software's basic functions and manipulating it can be done intuitively and fluidly using the NURBS based control points. The Grasshopper visual scripting interface ensures that more advanced volumes can be created and manipulated just as easily, with a low threshold for understanding programming and mathematics. In short, experimentation is cheap and adaptation

easy. This supports working intuitively with geometry for less computationally skilled architects and with code and scripts for more digitally minded architects. The shared mathematical basis in NURBS geometry allows for easy integration of ideas even though they might be generated in quite different ways. This enables a multiplicity of practices within a shared software environment, which encourages individual designers to experiment and bring own ideas and skill into the mix during early competition phases.

I interviewed Sean when he was doing form-finding experiments at the early stages of a six week competition project. He treasured the freedom within the team at the start of the competition as it gave him a chance to invest himself, his technical interests, and ideas into the process. Working alone for a couple of days, he utilised Grasshopper's capacity for integrating simulation of sunlight and wind to generate and evaluate potential forms that respond directly to relationships of the site in the project. It had been painstaking work with a steep learning curve and a lot of errors in the beginning: 'Part of design is you try something and 9 out of 10 times it does not work, or it looks like absolute crap,' he told me. When I asked how he kept going with those odds, he elaborated: 'Just today, I feel I got something that they liked, which is a pretty amazing feeling, something that seems to work, there is something about it that just seems to work at the site.' When I pressed him a bit on this, he replied: 'it just feels natural, it feels right. It seems to embody what it is that you believe in.'

The tension between collaboration and competition during early competition phases entices architects to put in extra time and take creative risks to develop their ideas with the understanding that a great idea might well become the creative impetus for a prestigious project. Early competition design practices are supported by the digital materiality of Rhino and Grasshopper, which enables quick ideation and advanced computational experimentation in the same software environment. This shared software environment which emphasise the showcasing of ideas in 3D geometry

ensures that input can be quickly evaluated by teams and project leads and inspiration can be shared in the team working to close deadlines. Ideas and concepts are evaluated from a substantive rationality, 'what feels right for the project' as Sean described it, the focus is on the end-goal, not who came up with the idea or how. This allows for integration of a input from architects with varying experiences, which as discussed in Chapter 6 and 7 is often embodied as tacit knowledge. This integration happens through processes of participatory sense-making when teams shift towards more egalitarian practices in impromptu huddles and meetings in front of screens to share and evaluate ideas.

Hierarchical patterns of interaction (high group / high grid)

Teams at 3XN and GXN can engage in hierarchical patterns of interaction. Examples can be seen when architects create modelling frameworks, define construction details, and maintain families of architectural components using the Revit software during project development.

Patterns of interaction

Once a competition or commission is won, the long hard work of developing competition proposals into materials for tender and construction begins. This work entails re-working of competition concepts while elaborating on structural construction, floorplans, façade detailing, materials, products, and interior design. The teams in Project Development are faced with moving a project through all these tasks with as few hiccups along the way as possible. Their output has to be both true to the original design and economically feasible. Project Development also have to manage client expectations as well as partnerships with expert collaborators to solve wicked design problems during years of development work. In 2017, I interviewed Torsten, an experienced 3XN Project Development architect, and asked him to describe the work he was doing. He explained:

> It is certainly as creative as thinking outside the box while in a competition. We have to really think about how we can realise projects and make price, time, and design come together. We have to make projects buildable without compromising the client's expectations. This is what is behind the notion of *What You See Is What You Get*, which we enforce as a bit of a hobby horse in the studio. What we promise up front is what we have to keep in the other end – this is what we do.

Project development teams have to work with the often conflicting demands of design, price, and time while elaborating on competition designs to the point where they can form basis for construction documentation and tendering processes. These many demands require a high degree of specialisation from members in the teams, Torsten explained:

> People have a specialisation, or they have been working continuously on a specific thing, ceilings, floor drawings, details, façade projects, or whatever. So there is a lot of knowledge, and a lot of experience. When you have worked with the same thing, you know what you get your hands into from the start when doing the next project … when setting a team you try to get this breadth [of specialisation] represented.

The focus on specialised roles leads to a high degree of accountability as specific architects often follow their part of a project through all the phases of development, having to resolve the problems that arise along the way. This leads to a more hierarchical organisation as Søren explained about his own role as project lead for the IOC:

> Project development becomes hierarchical in a way as it has longer timeframes. So my role evolves from being the first person on the project [from Project Development] going to meetings with Jan [Head of Design], and then growing the team for two years, and then having [one project development architect] on for a year, and then being more or less alone for the last year. It becomes hierarchical in the way that there is one recurring figure for the long haul which means that some degree of centralised knowledge cannot be avoided.

Just as Competition architects get to invest themselves in their project work, so do the architects in Project Development. Once the IOC was completed, I congratulated Laura on the look of IOC staircase, she replied:

> Thank you. When we went to see the completed IOC Headquarters, I was so excited because it is the first project I worked on that had been finished. I felt I had been intimately connected to

> the stair through all the testing of options and drawings and renders along the way. I knew from all the calculations exactly how high the handrails were at different points on the run of the stairs and how much head height would be above you to the next ring but it was impossible to know how it would feel to stand in the space. Nothing could have prepared me for the feeling of seeing the staircase in person, walking up it myself and understanding the impact it had on IOC employees and the other visitors to the building. It was truly a dream. I was so unbelievably proud to have been a part of it.

Owning part of a project during the long problem-solving phases of Project Development can be stressful but seeing the result take shape is highly exciting as well. Moving from concept to construction requires skill, precision, and accountability. While Competition teams encourage individual architects to take creative risks in order to produce an abundance of new ideas, teams in Project Development work creatively to solve wicked problems while minimising risks and imposing stability in projects. Søren, the IOC project lead explained:

> It is earlier than you might think that it becomes hard to make changes [to the design]. You cannot progress very far into a project before you have already shown some area numbers, prices have been estimated, the engineers have begun calculating principles, and you have shown all of this to the client.

This stability extends to the maintenance of a project's vision, ensuring that what clients have seen in competitions is also what they get in the finished building ('what you see is what you get,' as Torsten explained). And the stability extends to well-defined practices of project planning and costing to maintain this continuity of vision within budget constraints.

Søren explained how project planning and economy were two sides of the same coin:

> Project phases are defined in the Description of Services; feasibility study, project proposal… the names are different in Switzerland, but the phases are similar. They come with fairly precise definitions of what we need to do for each phase and at what level of detail. The Description of Services structure our work and our fee. So, if you are doing something other than what you ought to do in a phase you will get into trouble at a later stage. Do not fall behind schedule.

As a result, there is a lot of administration, communication, and clarification behind these practices. Jes, an architect with five years of experience as a Project Development lead explained:

‘In some periods we do a lot of design work, trying to create the right design solutions. At others it is mainly focused on securing the right agreements, project schedules, staffing, stuff like that.’ Like Torsten, Jes also highlighted the creativity inherent in this work but further described the attention to detail and rules it requires:

> Project Development needs the people who like to get deep into building code sections and clauses to find out ‘that this vision here [sketches quick detail from a competition project] needs another 50 millimetres to hold all the way to the finish line.’ We need those with more experience, with safety shoes and excel spreadsheets under their arms.

The procedural organisation of this work supports the long slog required to make a finished building on time and on budget. Work moves through defined phases as outlined by Søren with rules for what needs to be done when. Team leaders like Søren, Torsten, and Jes manage these phases and follow projects all the way through them. Søren again:

> On these large cases you might both be project architect and part of the overall project management team and therefore spending time away from the studio as I was in Switzerland. I was under pressure. It is a strain to have ten people working for you in Copenhagen if you are away one to two days a week and need to keep them busy. But roughly speaking your job is to lead and distribute work in relation to the team.

With time, project leaders come to build up a great deal of knowledge about the specific challenges and solutions of a project and become essential points of reference for decision-making. Digital experts like Laura and Kenn, who were responsible for modelling the IOC stairs and façade respectively, repeatedly referred to their close working relationship with the IOC project leaders when explaining how decisions were made during these processes. Laura elaborated on this relationship: ‘In terms of getting input from partners or the project leader, things were discussed, and then I tried them.’ This adherence to procedure and hierarchy comes with good reason. During project development, decisions set designs in stone – sometimes quite literally – and errors or

miscommunication can be extremely costly. During our interview, Enlai explained further how hierarchy in Project Development helped manage project risks:

> At a certain stage it is good to have a very strong hierarchy, because it makes everybody's lives easier if they have a clear set of decisions, and they follow those decisions. It also removes doubt and allow people to work more efficiently. There is a stage of design production whereby something is solidified to the point where you establish a hierarchy and then you follow it through and somebody in the end is responsible for the decisions made.

Modelling platform

The digital materiality of Revit supports the rule based work and hierarchical structure of Project Development practices. Torsten explained this in our interview Revit: 'I am not a software fanatic but at some stage you have to have directions for how to do things.' Chapter 5 described how Revit is set up to manage and maintain data as building projects develop. Geometry in Revit relies on up-front definition of elements and families. Once families are defined, they serve as stable data repositories, where information about elements, such as dimensions, can be updated once and extended to all elements of the same family in the building information model.

While developing the IOC case study, I talked about aspects of this work at length with several of the IOC architects and project leaders. Discussing early development of the parametric model for the IOC façade using five freeform curves for each side of the building, Kenn explained to me:

> To me the most important part of establishing the model was to find out what the key elements were. These were the twenty curves [describing the shape of the four facades] – five times four – and these we had to immediately interpret in Revit. When interpreting in Revit we have a demand for much more information. We have to explain: this curve here, where does it actually belong? It cannot just be a curve anymore. It has to have a surface, it has to have thickness, and we have to explain what it is connected to [in the database].

These procedural definitions are a lot more time consuming to establish than the plug and play form-finding enabled by Rhino and Grasshopper. But once elements and families have been created

in Revit, they are a lot more stable and allow teams to maintain and keep track of details amongst many collaborative partners. For complex 3XN projects such as the IOC, the hierarchical configuration of Revit is supported by the definition of an underlying building grid and data structure, which enables quick updating and exchange of parametric data within and beyond the studio. Kenn explained:

> We were beginning to receive a lot of information from the engineers and from manufacturers, from the client, from the local architect, and also from ourselves internally. It is obvious that when we are working in Rhino with a surface model that has zero thickness, we do not really get a full picture of how the building will actually be. All of a sudden we are getting thickness of windows, of all the elements. And this is where our model showed its strength as it could help us manage all the things coming in. In the model we could begin to explain from a data perspective, this surface here is x deep and x wide, and so on.

For design development and construction detailing of the IOC façade, the data structure was set up around a 3-dimensional building grid which allowed for locating each individual façade module. This established a data structure allowing for connecting and updating elements across the Revit-Rhino modelling environment. And this connection enabled rapid and continuous exchange of structured data-packages with collaborators such as façade engineers and structural engineers.

The hierarchical configuration of collaborative practice during project development is mirrored in the digital materiality and configuration of Revit building information models. This enable a procedural rationality, where decisions are made with reference to both organisational and digital hierarchies. Organisational hierarchies flow from the hands-on decision-making of project leaders. Digital hierarchies in the data-structure describing step by step relationships between e.g.: 1) core elements such as defining lines and surfaces, 2) building grid and data-tree; 3) buildings elements, families, and construction details.

Hierarchical modelling practices support the maintenance of stable architectural visions from competition to finished building. Hierarchies manages risks by distributing these across series of interlocking procedures with some redundancy between them. They enable stability in elements and

families in the digital model as these are being detailed and provide a steady framework for managing collaborative relationships in the studio and between studio and partners. Together these organisational and technical hierarchies allow architects to form stable relationships between teams, models, and collaborators, which enable creative and distributed problem solving during the long slog of project development.

Egalitarian patterns of interaction (high group / low grid)

Teams at 3XN and GXN can engage in egalitarian patterns of interaction. We see examples of this in the close collaboration that happens during in-depth design research when scripts and models become conduits for distributed deliberation about decisions and their consequences.

Patterns of interaction

During project development, 3XN teams sometimes face situations where the complexity of the problems in front of them requires close collaboration between a number of different experts to be solved. We saw a concrete example of this in the IOC project described in Chapter 8, when feedback from façade engineers and structural engineers led to the introduction of a double-skinned façade on the building. This introduced a host of unforeseen structural and aesthetic problems which could only be worked out in close collaboration between façade engineers, structural engineers, and architects at 3XN and GXN.

A key problem was the great variation of the spacing between inner and outer façades due to the dynamic design of the building. When discussing the project, Kenn vividly remembered moving façade sections back and forth within the Rhino model in an attempt to reconcile structural demands introduced by engineers with the overall aesthetics of the project. This work led to large gaps

between inner and outer skin, some of them with room for 'a full Copenhagen apartment,' as Kenn described it (p. 240).

A core requirement during project development is the maintenance of stability across teams, budgets, models, building elements, collaborative relationships, and architectural visions from competition to construction. Project Development architects Torsten and Jes explained that this entails a delicate balancing of price, time, and design as details are added to a project. But as Kenn told, the introduction of a double-skin facade threatened to introduce too much contradiction into these competing relationships in the IOC project: "Everything was curved. In all directions. We had to find a limitation." [37] Trade-offs between design language and construction detailing loomed large. Maintaining the studio mantra of *What You See Is What You Get*, while also incorporating structural feedback from engineers required much iteration of the façade design. As each section of the façade was unique and all elements computationally connected, developing construction detailing while managing iterations required control of a wide variety of parameters. Integrating these parameters while managing aesthetic concerns is an example of what I in Chapter 5 called 'complexity at a human meaningful scale.' We can now begin see that this complexity is not only mathematical but also social, requiring as much collective coordination as technical. Kenn elaborated:

> We are architects. There are always contracts for what a company like ours has to deliver. At some point we reach a stage where we as architects cannot, and will not, assume responsibility for a building. This is the façade engineers who assume this, the developers and so on, there are all these lines of responsibility. But we have taken on more responsibility and we have been double checking [geometry] several times. The façade engineers had the [3D] competences in-house but not the capacity to do this within the required timeframe, so we made an agreement that we delivered [the analyses] for them to build upon. And there, it is *there* that a lot of dialogue back and forth happened which has created this relationship of trust.

[37] Anthropologist Bryan Pfaffenberger (1992) argues that technologies require successful coordination of social and technical dimensions so that they work together and resist dissociation. Dissociation between social and technical actors – architects, engineers, models, and workflows – was exactly part of the challenge faced by the IOC project team.

This relationship of trust was created through ongoing exchanges around the façade between collaborators in the project. Ongoing research into digital modelling and workflows within GXN informed the process and to some extent the relationships described by Kenn capture the integration through situated sense-making of different skills and expertise in GXN research projects. Recall the Digital Factory project (Ch. 4) where architects, mathematicians and robotics experts had to work closely together to create a design to fabrication workflow. Or the Circularity Lab workshop (Ch. 7) where architects, engineers, and construction experts defined values and goals for a circular demonstrator pavilion. What is shared across these projects is the open-ended nature of the problems façade by the teams, and the fact that no single expertise or company could reconcile the divergent demands to a solution. Enlai, who was design lead on the Circularity Lab project describes the process:

> In that situation, it becomes clear when the group works together whose experience and skills are appropriate to guide what part of the process. That means that you do not have a boss, but you have multiple bosses. I don't believe that [hierarchy/leadership] necessarily has to happen dependent on how long you have been in a company, or who you are, or whether you own the company or not, it should come out of the process as a natural progression from the process.

Modelling platform

Deliberation and close collaboration were key to solving the wicked problems introduced by the double skin façade on the IOC Headquarters. The experience and skill needed to solve geometry, structural integrity, and construction detailing were distributed across multiple partners, including the project's façade engineers, structural engineers, and 3XN and GXN. The more egalitarian patterns of interaction between partners were enabled by the parametric modelling platform developed by the GXN Digital Design section for the project. The modelling platform enabled fast exchange and re-construction of data packages, sections, and principles between the 3XN team and façade and structural engineers. The well-defined data structure and computational basis of the

model meant that the 3XN team were able to deliver fast and reliable information for detailing by engineers in the form of sections, plans, and data packages. Engineers used these to develop construction principles. These principles where then sent back to the 3XN team in the form of localised mock-up details of select section of the façade. Kenn explained:

> They send this back [the localised mock-up detail] saying we believe this principle is doable. Ok, so we go into the model and update it so that it can manifest with the new principle, take it for a spin and come back with an evaluation and new suggestions – it was really very collaborative between us.

This iterative back and forth continued for several months, requiring a high output from all partners. During this process, the 3XN and GXN team constantly updated the digital IOC model. They used both Rhino and Revit to output data, and do structural and formal analysis to show how local design detailing would impact the full design expression of the building. This in turn enabled the engineers to iteratively fine tune their detailing of select sections while building an understanding of the dependencies of the overall façade design. And it allowed the 3XN team to adapt façade design while building a strong understanding of structural relationships in the building.

Constant exchange and analysis across several months allowed the full IOC project group to evaluate façade details, performance, and aesthetics across a large number of design iterations to find the best integration that could meet structural criteria while maintaining a dynamic design expression. Kenn elaborated on the significance of this process for the 3XN team:

> All of a sudden we are in there affecting the best suggestions of the engineers through a profile design or something or other which we would massage into the model to solve whatever challenge we were looking at. This is collaboration to me. And it meant that we as a company could really document our ability to drive these relationships with our collaborators.

When speaking to 3XN principals and project leaders involved with the IOC project they all described how the dynamic façade design of the project would have been impossible to realise without the modelling platform structuring geometry, data and collaboration with partners. They

also all underscored how the project had boosted their own and their collaborators confidence in the studio's ability to manage complex projects, and how this had paved the way for closer collaboration. The exchanges enabled by the modelling environment were crucial for building up trust early in the process and meant that 3XN could maintain control of the model and therefore also of the geometry of the project.

The more egalitarian configuration of these practices, when compared to other practices in Project Development, helped 3XN stay in control of their design in a situation where feedback from façade and structural engineers might otherwise have trumped their concerns with expressive geometry. Instead 3XN ran a collaborative and deliberative process, where decisions were made in a small team of close-knit collaborators based on critical appraisal of the consequences of various structural decisions.

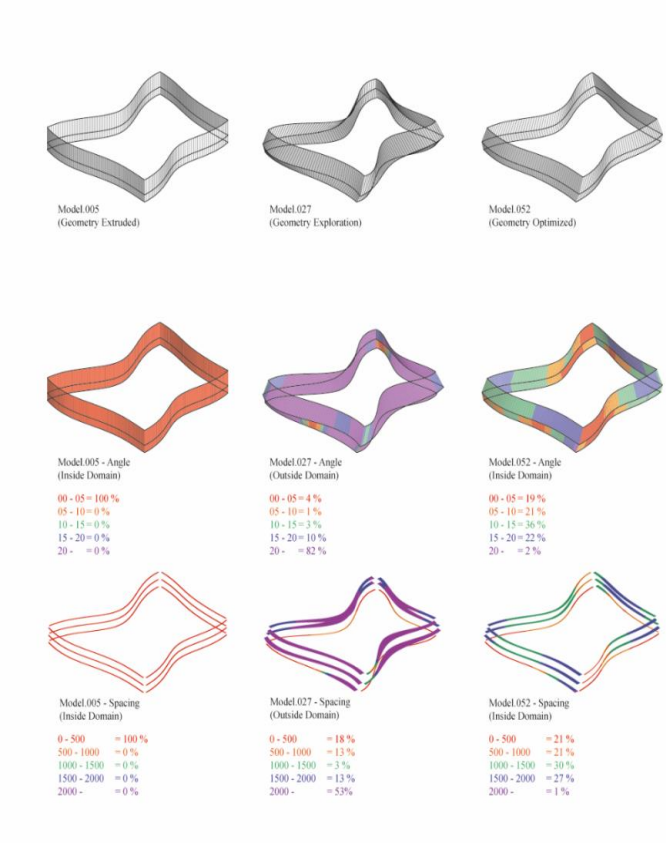

Fig. 9.2. Iterative design research into form (top row), angle (middle) and spacing (bottom) domains for the IOC façade. Comparative analysis across these domains allowed the project team to evaluate performance and aesthetics across a large number of design iterations.

The mutual trust and critical rationality inherent in this work was vitally dependent on the modelling platform encompassing Rhino, Revit and underlying data structure. This allowed for quick exchanges of exactly the data partners needed, when they needed it, as well as 3XN's evaluation of details in Revit and analysis of overall design expression in Rhino.

9.4 Stability and flux

I have discussed institutionalised patterns of organisation, rationality, and practice by following the phases of the IOC project at 3XN and GXN. This showed competitive ideation in early competition phases, hierarchical problem solving during project development, and more egalitarian design research drawing on expertise built up through software research in GXN. One might get the idea that the different project phases and departments are exclusively organised in these ways, but this is too simplistic. Interviews with architects in the competition department reveals relatively individualistic design research, such as Sean experimenting with fluid dynamics for form finding, but also that this mode of organisation can switch rapidly into deliberative participatory sense-making where the whole team gets involved. The switch is necessary for working out, evaluating, and integrating ideas under tight deadlines, as Dora also attested to. Similarly, Project Development entails both hierarchically patterned interactions, such as Laura working out the detailing of the IOC stairs with IOC project leaders, as well as prolonged deliberative interactions, as the consensus seeking design research surrounding the IOC façade.

These routine shifts corroborates Rayner's (1992) mobility hypothesis that individuals may move from context to context changing strategy with each new context. But what is moving here? The architects sit more or less still in front of their screens for much of this work. I argue that shifting relationships within the digital models play an important part in strategy switching at the

studio. My argument is that shifts can be effectuated through a change in relations in digital materiality. Creating digital models that span across several software and bespoke scripts means that the same model encompass several digital materialities and therefore several social affordances for interaction. Shifting these relations by shifting between software and filtering data in and out of the model allow the architects to introduce new interactional dynamics into their digitally mediated collaboration during the long slog from first designs to finished building.

This becomes most evident during Project Development, where the hierarchical nature of Revit's database configuration is used to structure hierarchical patterns of interaction around the detailing of building components and construction details. As Kenn pointed out, once a curve is exported to Revit, the digital materiality of the software demands that it be assigned to a family and receive spatial dimensions. Torsten and Jes pointed out that Project Development architects work with a high degree of specialisation, creativity, and accountability to be able to manage these details in the digital model, while Laura and Kenn explained that project leads have the final say and responsibility over these practices. However, this work can throw up problems that threatens to introduce too much contradiction into the competing relationships between design, price, and time on projects. In these cases, the parametric and associative logic of the data-driven modelling platform supports quick data-exchanges within the wider project group, which are necessary for enabling trusts and sense-making on a wider scale (see also Ch. 5).

In all these digitally mediated interactions, the interactions themselves come to form part of the unfolding situation, they both form part of their contexts and take on meaning from being embedded within larger institutional patterns of interaction. This conflation of dichotomies between action and context is also inherent in the argument of participatory sense-making (De Jaegher and Di Paolo 2007), situated action (Suchman 1987), material agency (Malafouris 2013) cognitive ecology (Hutchins 2010), and cultural theory (Rayner 1992, Douglas 1986). With this in mind, we

can say that pattering of data and digital interactions become part of the unfolding situations of design and constitutive of ecologies of mind.

The situated perspective of digital materiality highlights dynamic exchanges, but we must remember the central insight from Douglas that materially supported institutions create consistency in the flux of events surrounding us. How to balance stability and flexibility in these relationships throughout a project's lifetime is a core challenge for the architects at 3XN and GXN. In the anthropological discussion of dividuality, Mark Mosko described this dynamic between stability and flexibility well when he says: 'Every action – or transaction – is in this way both conventional and innovative.' (Mosko 2010:218) In the studio of 3XN and GXN we see that situated practices are conventional because they re-create and align technical and institutional patterns of interaction, and innovative because in doing so, they also create new possibilities for distributed interactions to meet the demands of shifting projects, problems, and collaborators. Following discussion about dividual personhood in Chapter 8, it should be clear that the institutional patterns described in the preceding section do not in any meaningful sense relate to types of people. We cannot go *'bird spotting'* and find *hierarchists* perched on their rightful trunk in the organisational forest, nor an *individualist* in wild flight, or a troop of *egalitarians* loudly proclaiming their allegiance to each other. What we might find however are *dividuals* engaging in contextually meaningful behaviour to enact possibilities for creative practice and collective mind. And these engagements create patterns of creativity and collaboration that are stabilised through digital materiality in the design studio.

Conclusion to chapter

A design project is, amongst other things, a series of socially shared shifts and shocks. In the studio of 3XN Architects and GXN Innovation, the modelling environment helps architects manage these

shocks more fluidly by connecting expertise and practices from across studio departments. A plurality of institutionalised patterns of practice and social mind come to co-exist, not by being merged into one collective muddle, but by existing as separate possibilities in the collective modelling environment.

In this way, applying the lens of digital materiality has shown how people coordinate themselves with their social, material, symbolic and technical environments in the context of overlapping ways of organising, reasoning and working together. We find shifting forms of relatively stable and meaningful patterns of interaction in 3XN and GXN as people engage shifting contexts and create dynamic relationships between social, technical, and material dimensions of the studio. The digital materiality of the modelling platform is continuously being reworked to change the context of creative practice and social mind at 3XN and GXN. In Chapter 5, I argued that the efficacy of the modelling environment at 3XN and GXN relies on the way it lets architects mix, rework, hide and bring forth specific relationships within the large parametric models they create. In the examples above, we have seen how the different collaborative practice in the studio are vitally dependent on the shifting materiality of the Rhino and Revit software, and their integration through underlying data structures and exchanges. The NURBS based control of geometry in Revit enable quick creation and manipulation of form, while the hierarchical families of Revit enable the control and maintenance of construction details for the myriad of components, everything from load-bearing columns to profiles on windows, that make up a building. The connection of these two environments through exchanges between geometry and data enables both stability and flexibility. It creates a stable notation system for maintaining close correspondence between the software environments as well as continuous flexible updating across them so that work carried out in one come to manifest in the other. The manipulation of this linked environment help anchor and subtly recast working relationships between the architects to enable interactional flexibility. I have argued

that these patterns of interaction themselves become part of mind and stabilise specific ways of collaborating and thinking about projects.

Conclusion

The emergence of computation in architectural design raises a number of questions as digital tools change not only the possibilities for creation of form, but also the workflows, business models, and future practices of the industry. Answers to these questions have reach well beyond the field of design as they require definition of our relationship with digital technology more widely.

Digitally minded architects at 3XN and GXN are understandably excited about the creative possibilities provided by the rise in computation within their industry and by new digital design environments that are so radically different from drawing which was long considered the sine qua non of architecture. But the architects I worked alongside also question what it means for them to be designing digitally and how digital tools change the nature of creativity, skill, and collaboration in the studio. These questions reveal a practical engagement with the relational framework I have sought to develop here, and the fact that we are, in the words of philosopher Bernard Stiegler (1998:152) 'prosthetic beings,' extending our creative capacities into the world around us through technics. Thinking about what this statement means when the prostheses we apply become environments in themselves, as 3D design software does in architecture, is a key motivation for my ethnography. To understand this, I asked how architects at 3XN and GXN established a sense of familiarity with digital design environments in order to work creatively with them in the larger context of architectural design projects. And I asked how the organisation, institutions, and practices of the studio came to entwine with digital tools to enable creative and social extension of mind at different time scales.

My argument throughout has been that answering these questions requires a shift in focus inwards into the configuration of the digital tools themselves and outwards from the tools to the relationship between tools and designers in the wider context of the 3XN and GXN studio.

I have approached the relationship between software and people with what anthropologist Don Ihde (1993:3) has called an "instrumental realism," taking the correlate between people and technology as the starting point for understanding creativity and collaboration in the architecture studio. This is underscored by a relational ontology that sees creativity and mind as enactive and social, dependent on material engagement and shifting interactional dynamics in the studio. The relational ontology developed throughout this thesis finds its analytical corollary in the concept of digital materiality. This concept has been informed by my ethnographic study of creativity and collaboration at 3XN and GXN, not least the questions asked by the architects. The riddle of: 'who designs, the architect, or the tool?' (p. 117-18) becomes a lot simpler to resolve if we recognise that neither architect nor tool design by themselves. Rather it is the architect + tool that designs, and do so within the highly socialised environment of the design studio.

The relational ontology at heart of this thesis is drawn from Material Engagement Theory (MET) and dynamic cultural theory. These approaches position themselves against dualisms such as mind and body, individual and community, action and context as well as the methodological individualism which can flow from these. Instead, MET and dynamic cultural theory forward a holism that sees mind as embedded and extended in the relations between people and their environments. To develop this perspective within the realm of software and design, I have explored productive overlaps between anthropology (Douglas 1986, Rayner 1992, Hutchins 2010, Bateson 1987[1972], Marriott 1976, Strathern 1988), enactivist philosophy of mind (Malafouris 2013, 2014, Rietveld & Brouwers 2016, Bruineberg & Rietveld 2019, Gallagher 2014, 2017, De Jaegher and Di Paolo 2007,), and situated studies of technology (Mauss 1973[1935], Suchman 2006, Ihde 1993, Hutchins 1995a, 1995b, Sigaut 2002, Malafouris 2014). From this, I developed the concept of digital materiality as an analytical framework for understanding how software and social organisation interweave to enable creative and social extension of mind at 3XN and GXN.

The interweaving of software, creativity and collaboration

At the studio of 3XN and GXN, design software is ubiquitous and digital models are used in all projects to integrate design research from several architects, keep track of the vast amounts of data that underlie 3D geometry, building detailing, and collaborative problem solving in architecture projects. What is qualitatively new in these tools, is the translation between geometry and data that makes the digital model more than an annotation of form and rather an environment for continuous computation of form. The shared informational basis for design models enables functional integration across a range of software and allows for manipulation, combination and re-use of input and outputs from these across all phases of architectural design and construction. In skilled hands, the strength of these 'tools to make tools' to paraphrase both the philosopher (Bergson 2005[1944]:154) and the architect (Burry 2011b:8), is vast. Yet, this strength also quickly becomes part of day-to-day realities of work at 3XN and GXN as shown by projects such as Digital Factory, CUBE Berlin, and the IOC Headquarters. To get below the surface of these day-to-day practices requires ethnographic engagement with the work and ideas of digital designers in the studio.

My ethnography details how digital modelling introduces a level of formal complexity into design practice, along with a more slippery understanding of form and scale when compared to physical models. Generating and working out ideas using computational models and scripts require a fine-grained feel for the digital materiality of various software, and the possibilities and constraints they give rise to. As I have argued, this 'feel' is borne from hours of embodied design research in the context of projects at the studio. Implicit in this argument is the fact that architects' understanding of digital tools and models borne from situated design research reaches well beyond the world of software to also encompass social mores and institutions in the studio which has shaped this learning.

Design software not only comes with *creative* challenges and possibilities, but also with *organisational* challenges and possibilities. Bridging across these is a prerequisite for successful teamwork at 3XN and GXN. As I have argued, collaborative interactional dynamics serve as scaffolding for the social extension of mind, and the very configuration of tools such as Rhino and Revit support different interactional dynamics – competitive and egalitarian interactions using the intuitive freedom of Rhino's NURBS curves to generate and evaluate a high number of ideas during competitions, hierarchical interactions using the well-defined data management structure of Revit to structure collaboration during project development. These are somewhat idealised instances and architects shift routinely between competitive, hierarchical, and egalitarian patterns of interactions in the context of projects. Indeed one of the strengths of the studio of 3XN and GXN lies exactly in the way it supports this possibility to switch between strategies.

With this in mind, I asked *what shifts* when interactions change at 3XN and GXN? My argument is that a shift can be effectuated through a change in relations in digital materiality. Creating digital models that span across several software and bespoke scripts means that the same model encompasses several digital materialities and therefore several social affordances for interaction. Shifting these relations by shifting between software and filtering data in and out of the model allows the architects to introduce new interactional dynamics into their digitally mediated collaboration during the long slog from first designs to finished building.

Creativity: material engagement and cognitive ecology

Digital materiality pays particular attention to the configuration of software and how they support some social interactions better than others. The argument of digital materiality thereby goes beyond most anthropological studies of architectural design by positing that if we want to understand the architect designing with 3D modelling environments, we have to understand how mathematical,

computational, and technical configurations of these environments come to shape patterns of interaction with the architect and between architects.

The Digital Factory project showed how a curve is not simply a curve in digital modelling practices, but dependent on the mathematical constructs used to describe its form and transform its shape. Building on observations of design research and interviews with project architects, I argue that the way geometry is encoded in software provides architects with different opportunities and constraints in their work at 3XN and GXN. Projects such as CUBE Berlin and the IOC Headquarters showed how the power of digital tools lies not only in the way their memory, speed and precision allow architects at the studio to control complex geometry, but also in their ability to combine a vast array of data at the scale of human perception and experience. Solving the technical integration of the 774 different glass panels that make up the CUBE Berlin façade would not have been possible without the power of digital models to handle vast amounts of data. Solving their aesthetic integration, evaluating how the total of 5.000 panels fit with local construction detailing and overall design language would not have been possible without the embodied skill of the architect for engaging the possibilities offered by digital models, certainly not as a some abstracted 'mental' exercise, which should somehow have gone before the action.

Instead digital materiality argues that creativity in digital modelling practice is a situated activity where mind emerges from dynamic interactions of people, materials, and technics and can never be the property of any of these elements alone. As we have seen, digital design requires some understanding of all of these realms. Embodied *material engagement* is where these come together to create meaningful connections through the ongoing sense-making between designer, tools, team, project, and studio. Through these couplings, the experience of embodied practice come to shape creative and social extension of mind in digital design.

I advanced the concept of *modelling platform* to describe the coupled nature of digital models at 3XN and GXN. A focus on platforms highlighted systemic interdependencies in models and their situations of creation and use. Drawing on anthropologist Edwin Hutchins' concept of *cognitive ecology* (2010, 2005, 2014), I argued that the designing mind extends through these interdependencies; mind is infused into technical, material, and social environments. Hutchins work shows that the cognitive properties of groups are different from the cognitive properties of the individuals in them, and that this difference is stabilised through a combination of organisational routines and material culture (Hutchins 2010, 2005, 1995a, 1995b).

In both platforms and cognitive ecology the key analytical focus is on interactions and dependencies between parts. By combining analysis of the development of a façade design for the CUBE Berlin project with exploration of different design software, I argued that the modelling platform comes to anchor cognitive ecologies at the studio through its ability to integrate different affordances of these software. In the 3XN and GXN studio, cognitive ecologies leverage the digital materiality of different software to enable selective cognitive blending of vastly different input and evaluation of the results at a human meaningful scale. In this perspective, modelling becomes a hybrid evolving practice comprising computational, aesthetic, and organisational factors interacting with each other to shape the extension of creative and social mind at 3XN and GXN.

The distributed perspective on cognition emphasises that the emergent properties of a cognitive ecology arise from the dynamic and continuous coupling of elements within it (Hutchins 2010). In the perspective of digital materiality, design thinking is empowered by the dynamics of specific modelling environments, models and workflows and creative agency becomes an emergent property, located not in the brain of the individual designer but in distributed transactions within larger cognitive ecologies. Using Lambros Malafouris' concept of *material agency* (Malafouris 2013:147, 2014) I analysed how the very materiality of their digital design tools mediate the

architects' possibilities for acting in the world. Agency in digital design is a relational and emergent product of digital material engagement. The digital materiality approach thereby combines insights from cognitive anthropology and philosophy of mind to open a new venue for the study of the relationship between technics, creative practice, and social innovation within design development.

Collaboration: dividuality and social mind

At 3XN and GXN the digital modelling platform forms a dynamic environment for integrating the results of a number of divergent design practices and logics, utilising the digital materiality of different software environments. As shown by the Circularity Lab and IOC Headquarter projects, wicked problems abound across all phases of architecture projects. These problems cannot be solved by any one person alone. Their meaning must be collectively defined, and their resolution requires merging of expertise from an array of skilled individuals.

Drawing on the work of Mary Douglas (1986, 1984[1966], 2003[1973], Douglas and Isherwood 1996[1979], see also Rayner 1986, 1992, 2006, Rayner and Malone 2001, Patel and Rayner 2012), I argued that a key problem for teams in the 3XN and GXN studio is creation of shared meaning in the form of architectural concepts that can serve as collective frames of reference for collaboration around wicked problems. The IOC project showed how design teams in the studio collaborate to pin down meaning in concepts that are stable enough to transmit shared meaning over the lifetime of a project, yet flexible enough to permit change as different forms of expertise come to inform this work. They anchor these concepts in digital scripts and models to work out the problems arising while developing projects into finished buildings.

I discussed examples of participatory sense-making during concept development and design of the Circularity Lab, and argued that this type of collaborative work, and hence social mind, is a

prerequisite for teamwork across the departments of 3XN and GXN. To further this argument, I discussed how architects do not enter design situations as individualised blank slates, but as dividuals (Marriott 1976, Strathern 1988, Mosko 2010, Pina-Cabral 2017) bringing a history of past and present entanglements that shape their expectations, experiences, and opportunities for creative and social extension of mind.

This argument linked design research and material agency with social aspects of sense-making and mind. As we saw on the IOC project – and heard in interviews with architects – digital models and scripts serve as conduits for establishing rich relationships between designers, their models, and the shifting teams, projects and studios they engage with. Formalising geometry in mathematical logic and creating a conduit for experimentation within the team, parametric models become a sort of coded substances flowing between persons to enable creative agency and social mind within the context of the studio.

As Douglas and other anthropologists remind us, people are participants in a fluctuating world where meaning and stability can only be achieved through collective work. The discussion of dividuality in digital design showed how material exchanges and technical conduits can become integral to this collective work. As both people and their digital scripts and models evolve through different social situations during the lifetime of a project, they become saturated in collective meaning, at once shaped by and shaping collaborative processes. This links my conception of dividuality to the dynamic strand of cultural theory forwarded by Steve Rayner (1992, Rayner and Malone 2001, Patel and Rayner 2012), and his analysis of how different social institutions come to shape people's capacity for thought and action. Rayner has made the case for a shift in social science from a focus on individuals to a focus on connections between them as the salient explanatory point. Considering the chapters in this thesis, I would argue that this focus should

extend beyond relations between people to relations between people, materials, and technics, which all form part of a rich and meaningful context for creative practice.

In the studio of 3XN and GXN, the modelling environment helps architects manage the shifts and shocks of design projects by connecting expertise and practices from across studio departments into single cognitive ecologies. Through analysis of the CUBE Berlin and IOC Headquarters, I argued that the efficacy of the modelling platform in 3XN and GXN relies on the way it lets architects mix, rework, hide and bring forth specific relationships within the large project they are developing. The manipulation of this linked environment helps anchor and subtly recast working relationships between the architects to enable organisational flexibility and dynamic shifts between institutionalised patterns of interaction. I have argued that these patterns of interaction themselves become part of mind and stabilise specific ways of collaborating and thinking about projects. A plurality of institutionalised patterns of interactions come to co-exist, not by being merged into one collective muddle, but by existing as separate possibilities in the extended socio-technical modelling environment. Architects coordinate themselves with their social, material, symbolic and technical environments in the context of overlapping ways of organising, reasoning and working together. In this sense, we find shifting forms of relatively stable and meaningful patterns of interaction in 3XN and GXN as people engage shifting contexts and create dynamic relationships between social, technical, and material dimensions of the studio environment.

The rise in digital technology is rapidly reshaping many aspects of our lives. For most of us, these developments outpace any deep understanding of their nature and impact. We live in a moment rich in technical invention, poorer in conceptual understanding. This raises serious epistemic issues for anthropology (and for architecture, design, and society more widely). The bewildering currents and counter-currents of our present moment calls for an open-minded,

interdisciplinary anthropology capable of investigating what technical change means for our understanding of natural and synthetic environments and for our interactions with technology and each other. I forwarded the architecture studio as a privileged site for examining these problems; privileged because contemporary architecture is both vitally dependent on digital technologies and actively engaging and modulating them. This double engagement allows us to peek over the architect's shoulder and into both the *configuration* and *meaning* of design software.

My argument has been that we must approach the increasingly complex digital aspects of human life and experience through two simultaneous analytical movements. One seeks to attend to the technics of digital design software and scripts, procedural steps and formal knowledge of how these systems operate. This part is indisputable, and too often it is missing from anthropological studies of design activity, and digital activity more widely, where configuration of technology is either down-played or black-boxed. But to avoid abstraction, the second movement must situate the study of digital technics and practice within the shifting social contexts of the design studio. The creative and social potential inherent in this dual move is a lesson, we can learn from the architects at 3XN and GXN. The relational perspective developed alongside them posits that mind is inextricably entwined with tools, people and environments; how we configure these relations are crucial for our opportunities to act and learn collaboratively. We should work to find better ways for understanding how digital tools can be leveraged positively to influence our shared possibilities for imagination, creativity, and social integration.

Bibliography

3XN Architects. (2013). *3XN Architects*. Seoul: Archilife.

Achinstein, P. (2011). *The Book of Evidence*. New York: Oxford University Press.

Agkathidis, A. (2016). *Generative Design (Form + Technique).* London: Laurence King Publishing.

Alač, M. (2011). *Handling Digital Brains: A Laboratory Study of Multimodal Semiotic Interaction in the Age of Computers.* Cambridge MA: MIT Press.

Alexander, C. (1964). *Notes on the Synthesis of Form.* Cambridge, MA: Harvard University Press.

Appadurai, A. (1996) *Modernity at Large: Cultural Dimensions of Globalization*. Minneapolis: U of Minnesota.

Aranda, B. and Lacsh, C. (2006) *Tooling*. New York: Princeton Architectural Press.

Archer, B. (1995) ”The Nature of Research.” *Co-design, interdisciplinary journal of design*. January, 6-9.

Arup. (2016). *The Circular Economy in the Built Environment*. London: Arup.

Arup and the Ellen MacArthur Foundation (EMF). (2018). *From Principles to Practice: First Steps Towards a Circular Built Environment.* London: Arup.

Arup and Ellen MacArthur Foundation. (2020). *From Principles to Practice: Realising the Value of Circular Economy in Real Estate.* London: Arup.

Aydin, C., Woge, M. G., Verbeek, P.P. (2019) ”Technological Environmentality: Conceptualizing Technology as a Mediating Milieu.” *Philosophy of Technology* 32, 321–338

Bachelard, G. (1994[1957]). *Poetics of Space.* Boston: Beacon Press

Baldwin, C. And Woodard, C.J. (2008) *The Architecture of Platforms, A Unified View*. Harvard Business School Working Paper. Boston MA.

Banke, T. (2013) *Parametri i Praksis: Generativ Performance i Arkitektur*. PhD Dissertation. Copenhagen: Royal Danish School of Architecture.

Bateson, G. (1932) ”Notes on a Snake Dance of the Baining.” *Oceania* Vol. 2, No. 3, 334-341

Bateson, G. (1958[1936]). *Naven: A Survey of the Problems suggested by a Composite Picture of the Culture of a New Guinea Tribe drawn from Three Points of View 2nd Edition*. Palo Alto: Stanford University Press.

Bateson, G. (1972). *Steps to an Ecology of Mind; Collected Essays in Anthropology, Psychiatry, Evolution, and Epistemology.* San Francisco: Chandler Pub.

Belardi, P. (2014). *Why Architects Still Draw: Two Lectures on Architectural Drawing*. Cambridge, MA: MIT Press.

Bergson, H. (2005[1944]). *Creative Evolution.* New York: Random House
Blanchette, J-F. 2011 "A Material History of Bits." *Journal of the American Society for Information Science and Technology.* Volume 62 Issue 6, 1042-1057.

Boellstorff, T. (2008). *Coming of Age in Second Life, An Anthropologist Explores the Virtually Human*. Princeton and Oxford: Princeton University Press.

Boellstorff, T. Nardi, B. Pearce, C. Taylor, T.L. (2012). *Ethnography and Virtual Worlds, A Handbook of Method*. Princeton and Oxford: Princeton University Press.

Boulding, K. E. (1966). "The Economics of the Coming Spaceship Earth." In H. Jarrett (ed.) *Environmental Quality in a Growing Economy*. 3-14. Baltimore, MD: Resources for the Future/Johns Hopkins University Press.

Bower, M. and Gallagher, S. (2013). "Bodily Affects As Penoetic Elements In Enactive Perception" *Phenomenology and Mind*, 4.1, p. 78-93.

Brand, S. (1968). *Whole Earth Catalog: Acces to Tools*. Courtesy of Kentucky Historical Society, (Pamphlet Fall 1968; 051 W628)

Brander, D. Bærentzen, J. A. Clausen, K. Fisker A.S. Gravesen, J. Lund, M. Nørbjerg, T., Steenstrup, K., Søndergaard, A. (2016) "Designing for Robotic Hot-Blade Cutting" In: *Advances in Architectural Geometry 2016*, p. 306-327, vdf Hochschulverlag AG an der ETH Zürich

Brander, D., Bærentzen, J.A., Fisker, AS. Gravesen, J. (2018) "Designing interactively with elastic splines" *Computer Aided Geometric Design* 62, 181–191

Bruineberg & Rietveld (2019). "What's Inside Your Head Once You've Figured Out What Your Head's Inside Of." *Ecological Psychology*, 31:3, 198-217

Buchanan, R. (1992). "Wicked Problems in Design Thinking." *Design Issues, Vol. 8, No. 2,* 5-21

Buchli, V. (2016). *An Archaeology of the Immaterial*. Abingdon: Routledge.

Buckminster-Fuller, R. (2008[1968]). *Operating Manual for Spaceship Earth.* Zürich: Lars Muller Publishers.

Burrell, J. (2009). "The Field Site as a Network: A Strategy for Locating Ethnographic Research." *Field Methods*, Vol. 21, No. 2, 181–199

Burrell, J.(2012) *Invisible Users: Youth in the Internet Cafés of Urban Ghana*. Cambridge, MA: MIT Press.

Burry, M. (1993). *Expiatory Church of the Sagrada Familia: Antoni Gaudi*. London: Phaidon.

Burry, M. (2005). “Homo Faber.” *Architectural Design* 75.4, 30-37.

Burry, M. (2011a). “Geometry Working Beyond Effect.” *Architectural Design* 81.4, 80-89.

Burry, M. (2011b). *Scripting Cultures: Architectural Design and Programming*. Chichester, UK: Wiley.

Burry, M. (2015). “Antoni Gaudí and His Role in Forming a Traditional Craft and Digital Culture Continuum.” In *2015 International Conference on Culture and Computing (Culture Computing)*, p. 3-9.

Burry, J. and Burry, M. (2010). *The New Mathematics of Architecture.* New York: Thames and Hudson.
Burry, J. and Burry, M. (2016). *Prototyping for Architects.* New York: Thames and Hudson.

Burton, J. (1983). ”The Ghost of Malinowski in the Southern Sudan: Evans-Pritchard and Ethnographic
Fieldwork.” *Proceedings of the American Philosophical Society*, Vol. 127, No. 4, 278-289

Carpo, M. (2011) *The Alphabet and the Algorithm*. Cambridge, MA: MIT.

Carpo, M. (2012) (ed.) *The Digital Turn in Architecture 1992-2012.* Chichester: John Wiley and Sons.

Chemero, A. (2003) ”An Outline of a Theory of Affordances.” *Ecological Psychology*, 15(2), 181–195

Clark, A. (2003). *Natural Born Cyborgs: Minds, Technologies, and the Future of Human Intelligence*. Oxford: OUP.

Clark, A. (2010) ”Material Surrogacy and the Supernatural: Reflection on the Role of Artefacts in ’off-line’ Cognition.” In Malafouris, L. Renfrew, C. (eds.) *The Cognitive Life of Things. Recasting the Boundaries of Mind.* Cambridge: McDonald Institute for Archaeological Research.

Clark, A and Chalmers, D. (1998). “The Extended Mind.” Analysis 58.1, 7-19

Clausen, K., Lineham, S., Lund, M., Rahbek, L., Poulsgaard, KS. (2020) ”New Workflows and Collaborations.” In Sheil, B., Thomsen, M., Tamke, M., Hanna, S. (eds) *Design Transactions. Rethinking Information Modelling for a New Material Age*. Lodnon: UCL Press.

Clowes, R. (2015). “Thinking in the Cloud: The Cognitive Incorporation of Cloud-Based Technology.” *Philosophy and Technology* 28.2, 261-296

Coleman, G. (2010) ”Ethnographic Approaches to Digital Media.” *Annual Review of Anthropology* 39, 487–505.

Coleman, G. (2012). *Coding Freedom, The Ethics and Aesthetics of Hacking*. Princeton and Oxford: Princeton University Press.

Coupaye, L. (2009) ”What’s the matter with technology? Long (and short) yams, materialisation and technology in Nyamikum village, Maprik district, Papua New Guinea.” *The Australian Journal of Anthropology* 20, 93–111.

Cross, N. (1982). “Designerly Ways of Knowing.” *Design Studies* 3.4, 221-27.

Cross, N. (2006). *Designerly Ways of Knowing*. London: Springer.

Davis, D. (2010) ”Untangling Grasshopper – Part 1: Design patterns.” Blogpost available here: https://www.danieldavis.com/untangling-grasshopper-part-1-design-patterns/ [last accessed 2020/04/20].

Davis, D. (2013a). ”A History of Parametric.” Blogpost available here: https://www.danieldavis.com/a-history-of-parametric/ [last accessed 2020/04/20].

Davis, D. (2013b). *Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture.* PhD Dissertation. Melbourne: School of Architecture and Design, RMIT University.

De Jaegher, H & Di Paolo, E. (2007). ”Participatory Sense-Making, An Enactive Approach to Social Cognition.” *Phenomenology and the Cognitive Sciences*. 6(4), 485–507

De Jaegher, H. Di Paolo, E. Gallagher, S. (2010). ”Can Social Interaction Constitute Cognition?” *Trends in Cognitive Sciences.* Vol. 14 No. 10, 441-447

de Rycke, K., Gengnagel, C., Baverel, O., Burry, J., Mueller, C., Nguyen, M.M., Rahm, P., Thomsen, M.R. (Eds.) (2018). *Humanizing Digital Reality, Design Modelling Symposium 2017*. Springer.

Deleuze, G. (1988) *The Fold. Leibniz and the Baroque.* London: Athlone Press.

Deleuze, G. (1992). “Postscript on the Societies of Control.” *October* 59, 3-7.

Descola, P. (2005) "On Anthropological Knowledge." *Social Anthropology* 13.1, 65-73.

Desjarlais, R. and Throop, C. J. (2011). “Phenomenological Approaches in Anthropology.” *Annual Review of Anthropology* 40, 87–102.

Deutsch, R. (2017). *Convergence. The Redesign of Design.* Chichester: John Wiley & Sons.

Dewey, J. (1999[1925]). *Experience and Nature (Carus Lectures).* Chicago: Open Court Press.

Dewey, J. (2009[1934]). *Art as Experience.* New York: Perigee Books

Di Paolo, E. (2009). “Extended Life.” *Topoi* 28, 9-21.

Dorst, K. (2011). “The Core of ‘Design Thinking’ and its Application.” *Design Studies* 32, 521-532

Douglas, M. (1984) [1966]. *Purity and Danger; an Analysis of Concepts of Pollution and Taboo*. New York: Praeger.

Douglas, M. (2003[1970]). *Natural Symbols. Explorations in Cosmology.* London and New York: Routledge.

Douglas, M. (2003[1973]). *Rules and Meanings. Mary Douglas: Collected Works, Volume IV.* London and New York: Routledge.

Douglas, M. (1986) *How Institutions Think*. Syracuse, NY: Syracuse UP.

Douglas, M. and Isherwood, B. (1996[1979]). *The World of Goods: Towards an anthropology of consumption.* London and New York: Routledge.

Dreyfus, H. (1992[1972]). *What Computers Still Can't Do: A Critique of Artificial Reason*. Cambridge, MA: The MIT Press.

Dyson, G. (2012) *Turing’s Cathedral. The Origins of the Digital Universe*. New York: Vintage Books.

Eastman, C. (1974). *An Outline of the Building Description System, Research Report no. 50*. Carnegie-Mellon University, Institute of Physical Planning. Pittsburgh, PA.

Edmonson, W. and Beale, R. (2008). “Projected Cognition – extending Distributed Cognition for the study of human interaction with computers.” *Interacting With Computers* 20, 128-140.

Ellen MacArthur Foundation (EMF). (2015). *Towards a Circular Economy: Business Rationale for an Accelerated Transition.* Available here: https://www.ellenmacarthurfoundation.org/publications/towards-a-circular-economy-business-rationale-for-an-accelerated-transition [last accessed 2020/03/21].

Ellen MacArthur Foundation (EMF), Sun, McKinsey. (2015). *Growth Within: A Circular Economy Vision for a Competitive Europe.* Available here: https://www.ellenmacarthurfoundation.org/publications/growth-within-a-circular-economy-vision-for-a-competitive-europe [last accessed 2020/03/21]

Evans-Pritchard, E. E. (1978[1940]). *The Nuer: A Description of the Modes of Livelihood and Political Institutions of a Nilotic People.* Oxford: Oxford University Press.

Farías, I. and Wilkie, A. (2015) (ed.) *Studio Studies. Operations, Topologies & Displacements*. Abingdon: Routledge.

Farin, G. E. (2002). A History Of Curves And Surfaces In CADG. In G. E. Farin, J. Hoschek, and M. Kim, *Handbook of Computer Aided Geometric Design*. p 1-22. Amsterdam: Elsevier.

Fauconnier, G, and Turner, M. (1998). “Conceptual Integration Networks.” *Cognitive Science* 22.2, 133-87.

Frayling, C. (1994). “Research in Art and Design.” *Royal College of Art Research Papers* 1:1.

Forward, K., Jensen, K., Pattullo, H. Taron, J. (2019). *Designing Out Waste: A Brief in Robotic Refabrication.* Laboratory for Integrative Design, University of Calgary

Gallagher, S. (2013). ”The Socially Extended Mind.” *Cognitive Systems Research* 25.26, 4-12.

Gallagher, S. (2014). “Pragmatic Interventions Into Enactive And Extended Conceptions Of Cognition.” *Philosophical Issues* 24, 110-126.

Gallagher, S. (2017). *Enactivist Interventions, Rethinking the Mind*. Oxford: OUP.

Garber, R. (2014). *BIM Design. Realising the Creative Potential of Building Information Modelling.* Chichester: Wiley.

Garber, R. (2017). *Workflows: Expanding Architecture's Territory in the Design and Delivery of Buildings.* Chichester: John Wiley and Sons.

Garfinkel, H. (1991[1967]). *Studies in Ethnomethodology*. Cambridge: Polity Press.

Gellner, D. And Hirsch, E. (2001). *Inside Organizations. Anthropologists at Work*. Oxford: Berg.

Gell, A. (1998) *Art and Agency: An Anthropological Theory*. Oxford: Clarendon.

Ghisellini, P. Cialini, C. Ulgiati, S. (2016). ”A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems.” Journal of Cleaner Production 114, 11-32.

Gibson, J. J. (1986) “The Theory of Affordances.” In. *The Ecological Approach to Visual Perception.* London: Lawrence Erlbaum Associates Publishers.

Gille, B. (1986). "Prolegomena to a History of Techniques." In: *The History of Techniques, Volume 1: Techniques and Civilisations*. New York: Gordon and Breach Science.

Gosden, C. (2008) "Social Ontologies." *Philosophical Transactions of the Royal Society B: Biological Sciences* 363.1499, 2003-2011.

Gramazio F & Kohler M (2008) *Digital Materiality in Architecture*. Zürich: Lars Müller Publishers.

Gunn, W (2002). *The Social and Environmental Impact of Computer Aided Design Technologies into an Architectural Design Process.* PhD Thesis. Manchester: Department of Social Anthropology, University of Manchester.

Gupta, A. and Fergusson, J. (1997) *Anthropological Locations Boundaries and Grounds of a Field Science*. Berkeley: University of California Press.

GXN and MCG (2018). “Circularity City: Shaping our urban future.” Available here: http://www.circularitycity.dk/publications/shaping-our-urban-future/ [last accessed 2020/03/21]

Harries-Jones, P. (2016). *Upside Down Gods: Gregory Bateson’s World of Difference.* New York: Fordham University Press.

Healey, P, and Rayner, S. (2009). *Unnatural Selection: The Challenges of Engineering Tomorrow's People.* London: Earthscan.

Heath, C. and Luff, P. (2000) *Technology in Action*. Cambridge: Cambridge University Press

Henschel, M. & Nilsson, F. (2015). *The Changing Shape of Practice: Integrating Research and Design in Architecture.* Routledge.

Hine, C. (2015). *Ethnography for the Internet: Embedded, Embodied and Everyday*. London: Bloomsbury

Hight, C. and Perri, C. (2006). “Introduction: Collective Intelligence in Design,” In Hight, C. and Perri, C. (eds.) *Collective Intelligence in Design.* Chichester: John Wiley and Sons.

Hopkins, O. (2018). “Architecture and the Paradox of Freedom.” In Hopkins, O. (ed.) *Architecture and Freedom: Searching for Agency in a Changing World.* Chichester: John Wiley and Sons.

Horst, H. A. and Miller, D. (eds) (2012). *Digital Anthropology.* Berg Publishers.

Houdart, S. and Minato, C. (2009) *Kuma Kengo. An Unconventional Monograph.* Paris: Éditions Donner

Hutchins, E. (1995a) *Cognition in the Wild*. Cambridge, MA: MIT Press

Hutchins, E. (1995b) “How a Cockpit Remembers its Speeds.” *Cognitive Science* 19, 265-288

Hutchins, E. (2005). “Material Anchors for Conceptual Blends.” *Journal of Pragmatics* 37.10, 1555-577.

Hutchins, E. (2010). ”Cognitive Ecology. *Topics in Cognitive Science* 2.4, 705-15.

Hutchins, E. (2014) ”The cultural ecosystem of human cognition.” *Philosophical Psychology*, 27:1, 34-49

Hutchins, E., Weibel, N., Emmenegger, C., Fouse, A., Holder, B. (2013). ”An integrative approach to understanding flight crew activity.” *Journal of Cognitive Engineering and Decision Making* 7(4), 353-376

Hutto, D. & Myin, E. (2013). *Radicalizing Enactivism. Basic minds without content*. Cambridge MA: MIT Press.

Hutto, D., Kirchhoff, M D. and Myin, E. (2014). Extensive Enactivism: Why Keep It All In? *Frontiers in Human Neuroscience Front. Hum. Neurosci.* 8, 1-11.

Ihde D. (1993). *Postphenomenology. Essays in the Postmodern Context*. Evanston: Northwestern University Press.

Ihde D & Malafouris L (2019) "Homo Faber Revisited: Postphenomenology and Material Engagement Theory." *Philosophy and Technology* 32(2), 195-214

Ingold, T. (2011). "Design Anthropology is not, and cannot be, ethnography." Copenhagen: KADK.

Ingold, T. (2013) *Making: Anthropology, Archaeology, Art and Architecture*. London: Routledge.

International Olympic Committee (IOC). (2020) *Maison Olympique / Olympic House.* Available here: https://architectureofthegames.net/new-ioc-headquarters/new-ioc-headquarters-maison-olympique-olympic-house-publication-by-the-ioc/ [Last accessed 20202/04/20].

Jensen, K. G. and Sommer, J. (2018). *Building A Circular Future 3rd Edition.* Copenhagen: GXN.

Ivarsson, J. (2010). "Developing the construction sight: Architectural education and technological change." *Visual Communication* 9(2), 171-191

Kallinikos, J. (2005) "The Order of Technology: Complexity and Control in a Connected World." *Information and Organization* 15, 185-202.

Kalmykova, Y. Sadagopan, M. Rosado, L. (2018). "Circular economy – From review of theories and practices to development of implementation tools." *Resources, Conservation & Recycling* 135, 190–201.

Kearle, M. (1988) "Review: How Institutions Think." *American Journal of Sociology*, Vol. 94, No. 1, 206-208

Kelty, C. (2008). *Two Bits. The Cultural Significance of Free Software.* Durham, NC: Duke University Press.

Khachab, C. (2016) "'What Does it Look Like?': On the Use of Intermediary Images in Egyptian Film Production", *Visual Anthropology Review*, 32(2), 168-180

Kiverstein, J., & Rietveld, E. (2018). "Reconceiving representation-hungry cognition: an ecological-enactive proposal." *Adaptive Behavior*. Vol. 26(4), 147–163

Klausen, T., & Hutchins, E. (1996). Distributed Cognition in an Airline Cockpit. In Engström, Y : Middleton, D. (eds.) (Ed.), *Cognition and Communication at Work.*

Kolarevic, B.(2003) (ed.) *Architecture in the Digital Age: Design and Manufacturing.* New York: Spon Press.

Korhonen, J. Nuur, C. Feldman, A. Birkie, S. E. (2018). “Circular economy as an essentially contested concept.” *Journal of Cleaner Production*. 175, 544-552.

Kreiner, K. (2002). “Tacit knowledge management: The role of artefacts.” *Journal of Knowledge Management*. 6, 2, 112-123.

Lambek, M. (2015). ”What’s love got to do with it?” *Hau: Journal of Ethnographic Theory* 5(1), 395–404

Lave, J. and Wenger, E. (1991). *Situated learning. Legitimate peripheral participation*. New York: Cambridge University Press.

Latour, B., and Woolgar, S. (1979). *Laboratory Life: The Social Construction of Scientific Facts*. Beverly Hills: Sage Publications.

Lawson, B. (1994). *Design in Mind.* Oxford: Taylor and Francis Ltd..

Le Corbusier. (1961[1954]). *The Modulor second edition*. London: Faber & Faber.

Lejerbo. GXN Innovation. Statens Byggeforsknings Institut. Foreningen for Byggeriets Samfundsansvar. (2018). *Circle House – Danmarks første cirkulære boligbyggeri.* Available here: http://www.buildingacircularfuture.com/book [last accessed 2020/03/21].

Lock, M. (1993). ”Cultivating the Body: Anthropology and Epistemologies of Bodily Practice and Knowledge.” *Annual Review of Anthropology*, Vol. 22, 133-155.

Lymer, G., Ivarsson, J. and Lindwall, O. (2009). “Contrasting the use of for presentation and critique: Some cases from architecture education.” *Computer-Supported Collaborative Learning* 4, 423-444

Lynn, G. (1993). “Folding in Architecture.” In Carpo (ed.) (2012) *The Digital Turn in Architecture 1992-2012*. Chichester: John Wiley and Sons.

Malafouris, L. (2013). *How Things Shape the Mind: A Theory of Material Engagement*. Cambridge, MA: MIT Press.

Malafouris, L. (2014). “Creative Thinging: The Feeling of and for clay.” *Pragmatics and Cognition*, 22:1, 140-158.

Malafouris, L. (2015). “Metaplasticity and the Primacy of Material Engagement.” *Time & Mind* Vol. 8, No 4, 351-371.

Malafouris, L. And Renfrew, C. (2010) (eds.) *The Cognitive Life of Things. Recasting the Boundaries of Mind.* Cambridge: McDonald Institute for Archaeological Research

Malinowski, B. (1932[1922]). *Argonauts of the Western Pacific. An Account of Native Enterprise and Adventure in the Archipelagoes of Melanesian New Guinea.* London: George Routledge & Sons LTD.

Mallgrave, H. (2010). *The Architect's Brain, Neuroscience, Creativity, and Architecture*. Wiley-Blackwell

Marcus, G. (1995). “Ethnography in/of the World System: The Emergence of Multi-sited Ethnography.” *Annual Review of Anthropology* 24, 95-117.

Marcus, G. (2013). ”Experimental forms for the expression of norms in the ethnography of the contemporary.” *HAU: Journal of Ethnographic Theory* 3 (2), 197–217.

Marriott, M. (1976). “Hindu Transactions: Diversity without Dualism.” In B. Kapferer (ed.) *Transaction and Meaning: Directions in the Anthropology of Human Issues.* p. 109-142. Philadelphia: Institute for the Study of Human Issues:

Marx, L. (2010). “Technology, The Emergence of a Hazardous Concept.” *Technology and Culture* 51(3), 561-577

Mauss, M. (2016[1925]). *The Gift. Expanded Edition.* Chicago: HAU Books.

Mauss, M. (1973[1935]). "Techniques of the Body." *Economy and Society 2.1*, 70-88.

Mauss, M. (1985[1938]) “A Category of the Human Mind: the Notion of Person; the Notion of Self.” In Carrithers, M., Collins, S., Lukes, S. (eds.). *The Category of the Person*. Cambridge: Cambridge University Press.

McKinsey (2016). “The circular economy: Moving from theory to practice.” *McKinsey Center for Business and Environment Special edition*, October 2016. Available here: https://www.mckinsey.com/business-functions/sustainability/our-insights/the-circular-economy-moving-from-theory-to-practice [last accessed 2020/03/21].

McKinsey Global Institute (2017) *Reinventing Construction. A Route To Higher Productivity*. McKinsey Global Institute, February 2017. Available here: https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/reinventing-construction-through-a-productivity-revolution [last accessed 2020/03/21].

Menary, R. (2010). ”Introduction the Special Issue on 4E Cognition.” *Phenomenology and the Cognitive Sciences* 9, 459-463.

Menges, A. and Ahlquist, S. (2011). *Computational Design Thinking*. Chichester: John Wiley & Sons.

Mindrup, M. (2019). *The Architectural Model. Histories of the Miniature and the Prototype, the Exemplar and the Muse.* Cambridge, MA: MIT Press

Mitchell, W. (2003). ”Design Worlds and Fabrication Machines.” In Kolarevic, B. (ed.) *Architecture in the Digital Age, Design and Manufacturing.* New York: Spon Press.

Mosko, M. (2010). ”Partible penitents: dividual personhood and Christian practice in Melanesia and the West.” *Journal of the Royal Anthropological Institute 16*, 215-240

Nader, L. (1972) ”Up the anthropologist: perspectives gained from studying up.” In Hymes, D. (ed.) *Reinventing Anthropology*. New York: Pantheon Books.

Naryan, K. (1993) ”How Native Is a "Native" Anthropologist?” *American Anthropologist, New Series*, Vol. 95, No. 3, 671-686.

Newell, A. Shaw, J. C., Simon, H. (1959). “The Process of Creative Thinking.” Presented at a *Symposium on Creative Thinking*, University of Colorado, Boulder, Colorado, May 16, 1958.

O'regan, J. K, and Noë, A. (2001). “A Sensorimotor Account of Vision and Visual Consciousness.” *Behavioral and Brain Sciences,* 24.05, 939-73.

Oxman, R. (2008). “Digital architecture as a challenge for design pedagogy: theory, knowledge, models and medium.” *Design Studies* 29, 99-120.

Oxman R. (2017). “Thinking difference: theories and models of parametric design thinking.” *Design Studies* 52, 4-39

Pallasmaa, J., Malgrave, H. F., Arbib, M., (2013) *Architecture and Neuroscience*. Espoo: Tapio Wirkkala Rut Bryk Foundation

Parme, S. (2018). *How do Master Planners Think? A Sociomaterial Inquiry*. DPhil thesis. Oxford: Institute for Science Innovation and Society, University of Oxford.

Patel, T., and Rayner, S,. (2012). "Towards a Transactional Approach to Culture: Illustrating the Application of Douglasian Cultural Framework in a Variety of Management Settings." *European Management Review* 9.3, 121-38

Picon, A (2010). *Digital Culture in Architecture: An Introduction for the Design Professions*. Basel: Birkhäuser.

Piegl, L. And Tiller, W. (1997). *The NURBS Book, Second Edition*. Heidelberg: Springer Verlag.

Pina-Cabral, J. (2017). *World: An Anthropological Examination.* Chicago: Hau Books.

Pfaffenberger, B. (1992). “Social Anthropology of Technology.” *Annual Review of Anthropology*, Vol. 21, 491-516

Polyani, M. (2009[1966]). *The Tacit Dimension*. New York: Doubleday & Co.

Poulsgaard, KS. (2017). “Enactive individuation: Technics, temporality and affect in digital design and fabrication.” *Phenomenology and the Cognitive Sciences*, 1–18

Poulsgaard, KS. and Clausen, K. (2018). “Modelling Workflow: Data, Collaboration, and Dynamic Modelling Practice.” In De Rycke et al. *Humanizing Digital Reality: Design Modelling Symposium Paris*

Poulsgaard, KS. and Malafouris, L. (2017). “Models, Mathematics and Materials in Digital Architecture.” In Cowley, R., and Vallée-Tourangeau, F. (eds.) *Cognition Beyond the Brain, Computation, Interactivity and Human Artifice, 2nd Edition.* Springer.

Poulsgaard, KS. and Malafouris, L. (forthcoming). ”Understanding the hermeneutics of digital materiality in contemporary architectural modelling: A material engagement perspective.” *AI and Society* forthcoming.

Rabinow, P., Marcus, G., Fabion, J., Rees, T. (2008). *Designs for an anthropology of the contemporary.* Durham, NC: Duke University Press.

Rasmussen, S. E. (1957). *Om at Opleve Arkitektur*. Copenhagen: Arkitektforeningen.

Rayner, S. (1982). “The Perception of Time and Space in Egalitarian Sects: A Millenarian Cosmology.” In M. Douglas (Ed.), *Essays in the Sociology of Perception*. p. 247–274. London: Routledge & Kegan Paul.

Rayner, S. (1986). “Management of Radiation Hazards in Hospitals: Plural Rationalities in a Single Institution.” *Social Studies of Science.* Vol. 16, No. 4, 573-591

Rayner, S. (1991). “A cultural perspective on the structure and implementation of global environmental agreements.” *Evaluation Review* 15.1, 75-102.

Rayner, S. (1992). “Cultural Theory and Risk Analysis” in Krimsky and Golding (eds.). *Social theories of Risk.* London: Praeger.

Rayner, S. (2004). “The Novelty Trap: Why Does Institutional Learning about New Technologies Seem So Difficult?” *Industry and Higher Education* 18(6), 349–355.

Rayner, S. (2006) ”Wicked Problems: Clumsy Solutions – diagnoses and prescriptions for environmental ills.” Jack Beale Memorial Lecture on Global Environment, ANSW Sydney, Australia, July 2006. Available here: http://eureka.sbs.ox.ac.uk/93/ [Last accessed 2020/04/20].

Rayner, S. (2012). “Uncomfortable knowledge: the social construction of ignorance in science and environmental policy discourses.” *Economy and Society* 41:1, 107-125

Rayner, S. and Malone, E. (2001). “Climate change, poverty, and intragenerational equity: the national level.” *Int. J. Global Environmental Issues* Vol. 1, No. 2, 175-202

Rietveld, E. (2016). ”Situating the Embodied Mind in a Landscape of Standing Affordances for Living Without Chairs: Materializing a Philosophical Worldview.” *Sports Med*. 46, 927–932.

Rietveld, E., & Brouwers, A., (2016). ”Optimal grip on affordances in architectural design practices: an ethnography.” *Phenomenology and the Cognitive Sciences*. 16, 545–564

Rietveld, E. and Kiverstein, J. (2014). ”A Rich Landscape of Affordances.” *Ecological Psychology* 26, 325–352.

Rittel, H. and Webber, M. (1973). “Dilemmas in a General Theory of Planning.” *Working Papers from the Urban & Regional Development.* p. 155-169. Berkeley: University of California Berkeley.

Robbins, E. (1994). *Why Architects Draw*. Cambridge, MA: MIT.

Rowe, P. G. (1982). “A Priori Knowledge and Heuristic Reasoning in Architectural Design.” *Journal of Architectural Education* 36:1, 18-23

Rowe, P. G. (1991[1987]). *Design Thinking.* Cambridge MA: MIT Press.

Rowe, P. G. (2017). *Design Thinking in the Digital Age.* Harvard MA: Sternberg Press.

Ryle, G. (1949). *The Concept of Mind.* Chicago: University of Chicago Press.

Schumacher, P. (2008) ”Parametricism as Style. Parametricist Manifesto” Presented at *the Dark Side Club, 11th Architecture Biennale, Venice.*

Schatzberg, E. (2018). *Technology. Critical History of a Concept.* Chicago: University of Chicago Press.

Schön, D. (1983). *The Reflexive Practitioner*. New York: Basic Books.

Schram, R. (2015). ”A society divided. Death, personhood, and Christianity in Auhelawa, Papua New Guinea” *Hau: Journal of Ethnographic Theory* 5(1), 317–337

Sigaut, F. (2002) “Technology” In: Ingold, T. (ed). *Companion Encyclopaedia Of Anthropology*. London: Routledge.

Simon, H. A. (1996[1969]). *The Sciences of the Artificial.* Cambridge, MA: MIT Press.

Simon, H. A. and Newell, A. (1971). “Human Problem Solving: The State of Theory in 1970.” *American Psychologist*, 145-159.

Smith, A. (2004). *Architectural Model as Machine. A New View of Models from Antiquity to the Present Day.* Oxford: Architectural Press.

Spradley, J. (1979). *The Ethnographic Interview.* New York: Holt, Rhinehart and Winston.

Star, S. L. (1999). "The Ethnography of Infrastructure." *American Behavioral Scientist* 43.3, 377-91.
Stiegler, B. (1998). *Technics and Time, 1: The Fault of Epimetheus*. Stanford, CA: Stanford UP.

Strathern, M. (1988). *The Gender of the Gift. Problems with Women and Problems with Society in Melanesia.* Berkeley: University of California Press.

Suchman, L. (1987). *Plans and Situated Actions: The Problem of Human-Machine Communication*. Cambridge: Cambridge University Press

Suchman, L. (2006). *Human-Machine Reconfigurations. Plans And Situated Actions 2nd Edition*. Cambridge: Cambridge University Press.

Suchman, L. (2011). "Anthropological Relocations and the Limits of Design." *Annual Review of Anthropology* 40, 1–18.

Suchman, L. & Trigg, R. (1995). "Understanding Practice: Video as a Medium for Reflection and Design." In Baecker, R. Grudin, J. Buxton, W. Greenberg, S. (eds.) *Readings In Human-Computer Interaction*. Elsevier.

Sussman and Hollander (2014). *Cognitive Architecture: designing for how we respond to the built environment*. New York: Routledge/Taylor & Francis Group.

Sutherland, I. (2003[1963]). *Sketchpad: A man-machine graphical communication system*. University of Cambridge Computer Laboratory Technical Report Number 574.

Sutton, T. (2017). "Our Virtues and Devices: Exploring the Digital Detox" In: Bartlett, V. and Bowden-Jones, H. (eds.) *Are We All Addicts Now? Digital Dependence*. Liverpool: Liverpool University Press.

Sylvest, M. (2017). *Situated Social Aspects of Everyday Life in the Built Environment Informing the Design Process by Expanding Theory and Evaluation Methods Related to Social Interactions in Designed Physical Settings.* Ph.D. Dissertation. Roskilde: Department of Humans and Technology, Roskilde University.

Søndergaard, A. And Feringa, J. (2017) "Scaling Architectural Robotics: Construction of the Kirk Kapital Headquarters." In Menges, A., Sheil, B., Glynn, R., Skavara, M. (eds.) *Fabricate 2017.* London: UCL Press

Søndergaard, A., Feringa, J., Nørbjerg T., Steenstrup, K., Brander, D., Gravesen, J., Markvorsen, S., Bærentzen, A., Petkov, K., Hattel, J., Clausen, K., Jensen, K., Knudsen, L., and Kortbek, J. (2017) "Robotic Hot-Blade Cutting, An industrial approach to cost-effective production of double curved concrete structures" In: *Robotic Fabrication in Architecture, Art and Design. Proceedings of RobArch 2016*, Reinhardt, D., Saunders, R., Burry J. (Eds.), Springer, 2016, 150-164.

Tedeshi, A. (2015). *AAD_Algorithms-Aided Design: Parametric Strategies Using Grasshopper*. Napoli: Edizioni Le Penseur.

Terzidis, K. (2006). *Algorithmic Architecture*. Oxford: Architectural.

Thompson, E. (2007). *Mind in Life. Biology, Phenomenology, and the Sciences of Mind.* Cambridge, MA: Harvard University Press.

Thompson, M. (2008). *Organising and Disorganising: A Dynamic and Non-linear Theory of Institutional Emergence and Its Implications.* Bridport: Triarchy Press.

Thompson, M., and Rayner, S. (1998). ”Cultural discourses. The Societal Framework,” In: S. Rayner and E. L. Malone, (Eds)., *Vol. 1, Human Choice and Climate Change*. p. 265–343. Columbus: Battelle Press.

Tomasello, M. (1999). *The Cultural Origins of Human Cognition.* Cambridge, MA: Harvard University Press.

Tsing, A. (2000) ”The Global Situation.” *Cultural Anthropology*, 15, 3, 327-360

United Nations Environment Programme (UNEP). (2010). “Greening Cement Production has a Big Role to Play in Reducing Greenhouse Gas Emissions.” *UNDEP Global Environmental Alert Service (GEAS).* Available here: https://www.unenvironment.org/resources/report/greening-cement-production-has-big-role-play-reducing-greenhouse-gas-emissions [last accessed 2020/03/21].

Varela, F. J., Thompson E., and Rosch, E. (1991) *The Embodied Mind: Cognitive Science and Human Experience.* Cambridge, MA: MIT Press.

Venturi, R. (1966). *Complexity and Contradiction in Architecture.* New York: Museum of Modern Art.

Verweij, M., Douglas, M., Ellis, R., Engel, C., Hendriks, F., Lohmann, S., Ney, S., Rayner, S., Thompson, M., (2006) ”Clumsy Solutions for a Complex World: The Case of Climate Change.” *Public Administration* Vol 84(4), 817-843

Vitruvius (2009). *On Architecture.* London: Penguin Classics

Vinck, D. (ed.) (2003). *Everyday Engineering, An Ethnography of Design and Innovation*. Cambridge, MA: MIT Press.

Wainwright, O. (2018). ”Snubbed, cheated, erased: the scandal of architecture’s invisible women.” *The Guardian* 2018/10/16. Available here: https://www.theguardian.com/artanddesign/2018/oct/16/the-scandal-of-architecture-invisible-women-denise-scott-brown [Last accessed 2020/03/20].

Weiss, K. L. (2017). *Adventures in Conceptualism.* Stokholm: Arvinius + Orfeus

Winograd, T., & Fernando F. (1986) *Understanding Computers and Cognition: A New Foundation for Design*. Boston: Addison-Wesley Professional.

Whitehead, A. N. (1913). “Presidential Address to the London Branch of the Mathematical Association.” *The Mathematical Gazette,* Vol. 7, No. 104, 87-94.

Woolgar, S. (1991). "Configuring the User: The Case of Usability Trials." In: Law, J. (eds.). *A Sociology of Monsters: Essays on Power, Technology, and Domination.* p. 57-102. London: Routledge.

World Economic Forum (WEF). (2018). “Circular Economy in Cities: Evolving the model for a sustainable urban future.” Geneva: World Economic Forum.

Yaneva, A (2009a). *Made by the Office for Metropolitan Architecture: An Ethnography of Design*. Rotterdam: 010 Publishers.

Yaneva, A. (2009b). *The Making of a Building, A Pragmatist Approach to Architecture*. Bern: Peter Lang AG International Academic Publishers.