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Material Control: Reflections on the social and material practices of digital fabrication

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ABSTRACT
Digital fabrication and its impact on design has been a burgeoning area of research for over two decades, and it now appears to be transitioning into a phase beyond mere fascination with complex and seductive geometry. The technology continues to proliferate, new tools such as 3D printers emerge, new materials are developed and the scale of fabrication increases. In addition, robotics and computer numerical controlled routers are increasingly used for fabrication and assembly processes in a wide range of new domains. This paper has two objectives. The first is to situate digital fabrication within a historical narrative where design and technology are entangled in order to shed light on how design technologies are complicit in social practices. Second, through original research, I unpack design and digital fabrication processes, analyzing their materiality and the impact on knowledge practices. Evidence suggests that design and making professionals are adopting new organization and social practices. Ultimately, I argue that as design processes transition into the immateriality of the Cloud, materiality is more important than ever.

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Introduction

Materiality is conspicuous in both its presence within, and absence from, narratives on digital fabrication. In this paper I draw from different cultural territories to unpack this phenomenon: my own practical research on design and digital media, the history of design descriptions and the contemporary rendering of digital fabrication. The claim that tools for design and making of space are entangled with social practices within those spaces is evidenced in Evan's *Translations from Drawings to Buildings* (1997), in which he illustrates how drawing – a tool for representation – evolved in conjunction with habits that are themselves being changed by socio-economic forces. For example, during the eighteenth century we saw a shift from classical spatial plans where each room has a single formal function, to a more liberal social condition and harsher economic climate where rooms evolved to support multiple functions. Here, drawing typologies emerge that are strange concoctions and combinations of developed surface drawing and furniture in perspective floating around an orthogonal plan. I will explore this bizarre and grotesque phenomenon in some depth in a

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subsequent section, as a demonstration of how the techniques that evolve to utilize tools and materials are entangled with the habits and routines associated with them. With digital fabrication, particularly 3D printing, becoming mainstream and already creating new spatial typologies, I ask how this might impact social and material practices.

Tony Stark: 'Hey, I like it, fabricate it, paint it.'

Jarvis: 'Commencing automated assembly, estimated completion time 5 hours.'

Tony Stark: 'Don't wait up honey…'

In popular culture, making and manufacture are often hidden from the public. Buildings are hidden under a plastic or canvas skin while they are under construction or renovation; workshops are invariably hidden from sight in basements. However, science fiction has a more romantic vision to challenge these contemporary examples. For example, the above quote is an exchange from the film *Iron Man* (2008), where Tony Stark, played by Robert Downey Jr., is talking to Jarvis, the artificial intelligence that manages his workshop. It perhaps serves as the example par excellence of aspirations surrounding digital fabrication, in which designs are materialized without compromise by real-world manufacturing practices, knowledge or limitations. Making is hidden, hermetically sealed somewhere within Stark's home, and the audience is never privy to it. Can we argue that the reality of digital fabrication is delivering on the imagined aspirations of earlier techno-romantic visions, such as *Star Trek*'s Holodeck or Replicator? Perhaps not, as retail corporations such as ASDA and Staples have tried and failed to fold 3D printers into their consumer framework. I argue that material knowledge remains complicit in making with these new technologies. The quotation above from *Ironman* is preceded by technical dialogue on materiality, implying that Tony is a virtuoso of fabrication. Later, in *Ironman 2* (2010), we see Mr. Stark literally 'hacking' his home as he enters 'hardware mode.' This narrative suggests that significant material knowledge continues to be present for making, even with Tony Stark's impressive automated fabrication facility. In fact, many of the real-world working environments in which we find these technologies – labeled makerspaces, or hackerspaces – feel semi-industrial, the diametrical opposite of consumer retail environments. Technological, grotesque bodies and parts (Figure 1) litter the environment as makers and hackers experiment with materiality and production. In this regard, they have little in common with retail spaces that are designed for consumption. Makerspaces share more in common with laboratories and workshops, which are places of experimentation and production. Understanding materiality involves breakage, accident and failure; the process is as grotesque as it is romantic. Consequently, it does not resonate with the sterile models of mainstream consumption, which present packaged objects for consumption and hide the process by which they are brought about.

In this respect, the digital fabrication phenomenon resonates with the industrial or machine age, as well as theoretical concepts such as dirt (Bakhtin and Iswolsky 1984; Douglas 1978), newness (Monod and Wainhouse 1974) and consolidation (Deleuze and Guattari 2004), which I have explored elsewhere in regards to design, communication and making (McMeel and Coyne 2004; McMeel, Coyne, and Lee 2005). Thus, we are not without theoretical grounding that links materiality, innovation and, indeed, the grotesque. In fact, some of the spatial configurations or makerspaces that are emerging hand in hand with these technologies are synonymous with dirt, the consolidation of unexpected skills and the production of new innovations. Later in this paper, I will explore the significance of popular culture for

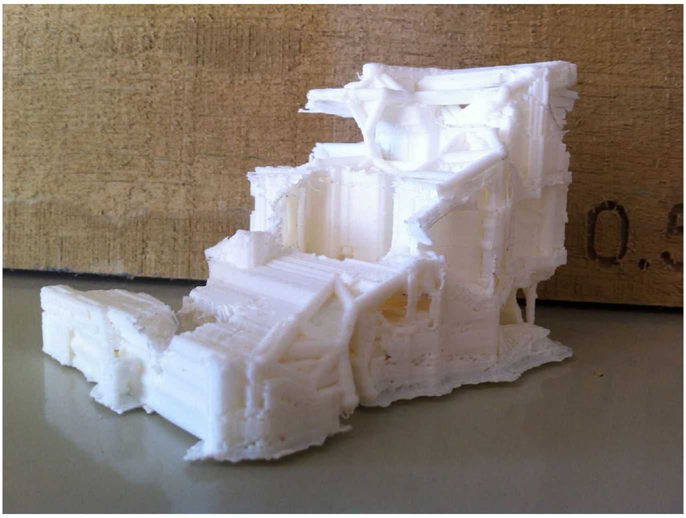

Figure 1. Grotesque 3D print where scaffolding is fused and indistinguishable from the form.

both selling and buying into a conception of these technologies delivering clean immaterial materialization.

I will eventually offer my own research in design and digital media to shed light on the intimate changes being heralded by digital fabrication. Conventions for design descriptions are constantly being challenged – we know this much from Evans (1997). In the contemporary design landscape, parametric tools provide new ways of encoding, describing and interacting with design. Tools and spaces are being challenged and asked to validate themselves within this highly dynamic design context, and it is within this context that new systems and social habits emerge. It is through early adopters that we gain perspective on the consequences of emerging phenomena, such as digital fabrication.

History

As mentioned briefly in the introduction, the causal relationship between tools for making and societal change is not without precedent. In this section, I will explore this claim in more depth to help delineate the relationship between tools of production and spatial practice.

During the Industrial Revolution, towns formed around factories, which were the catalysts for employment and ultimately settlement and urbanization. The subsequent Information Revolution and demand for while-collar skills saw these regional centers drained of people as market forces caused them to gravitate towards population centers (Rifkin 2011); in the words of McLuhan (1994, xxi), 'first we make the tools and thereafter they make us.' As illustrations of a technological paradigm intertwined with societal change, these are perhaps obvious, although given that societal processes are highly complex it would be overly simplistic to argue that the results are easy to predict. If we conceive of any given process as what Wenger calls 'constellations of practice' (Wenger 1999), this metaphor suggests highly interdependent and dynamic systems in which small changes can have significant and unexpected consequences. Thus, predicting precise causality and ensuring a desired outcome is problematic. Conversely, technological change can fail to live up to its hype. For example, there has been a dramatic increase in the provision of co-working offices throughout cities. These environments provide spaces and resources for anyone to rent, book and use flexibly. They hold the promise of radically altering both the workplace and how we organize our work/life balance. They are fundamentally an extension of hot-desking, which is itself part of an evolution of practice that can be traced back to tele-working, a concept from the 1970s. Arguably none of these lived up to the hype, although they have heralded change in both work habits and the design of spaces to accommodate those habits. While an over-reliance on the postwar work week is occasionally found culpable for hindering innovation, I would propose, as a designer, that recent innovations in office design by Cisco and Google suggest we are still learning about work habits and habitats (Cohen 2014; Wainwright 2013). Rather than the interplay of work habits and habitats being mapped with some certainty, they continue to evolve and be influenced by emergent technologies.

In search of further evidence, I offer Evans' exploration of domestic architecture (Evans 1997). Using Villa Madama, designed by Raphael in the sixteenth century, Evans demonstrates how architecture can be seen to support activities, albeit very prescribed activities that follow a formal narrative. Later, the modernists affected an important shift in this relationship by framing the home as a 'machine for living.' The object that is the home now occupies center stage, and activities become subservient to habitat. This relationship is further complicated through changing socioeconomics and politics. In drawings of Palladio's Villa, such as the Villa Madama, also from the sixteenth century, we see the classic matrix of rooms, no corridor spaces or ornamentation features within the drawings. Each room had a distinct function and social convention and often dictated a narrative that moved people from room to room. By the seventeen century, corridors featured in the home as privacy became elevated in importance. By the eighteenth century, alongside the ornamentation and decoration favored by the late Baroque or Rococo period, the 'developed surface' drawing technique had evolved. Drawings featured texture, details and ornamentation on surfaces, as well as pieces of furniture around the edges of spaces. However, at the turn of the nineteenth century we see a breakdown between spatial ontology and tools for drawing and representing space. Due to habitual changes caused by changing socioeconomics during this period, we see rooms evolving from hosting a single function to accommodating multiple functions. A drawing by Gillow and Co. (1831) from that period demonstrates the difficulty in describing multi-function spaces with conventional plan and elevational drawing grammar from that period. The result is a conventional orthogonal plan describing the dimensions and shape of the space, surrounded by similarly conventional projected developed surface drawings describing the surface treatment and ornamentation featured on the walls. However, much more difficult is adding furniture in quite specific locations around the space. The period drawing convention for furniture is perspective, and the resultant drawing is an uncanny concoction of orthogonal, developed surface and perspective drawing, where the furniture can be seen drawn in sideways and upside down perspective within the orthogonal plan.

This brief historical review helps to support the proposition that tools and materials, be they pencils, paper or 3D printers, are not benign. They are devices that privilege particular outcomes and ways of working and obfuscate others; even in the hands of craftsmen and virtuosos of design, as we have just discussed. In this regard, it is useful to situate these tools within communication theories, such as generative metaphor (Schön 1979) or wicked problems (Rittel and Webber 1973), where there are persuasive arguments claiming that particular ways of describing privilege certain outcomes. This discourse has more recently been extended into design by Richard Coyne (2005), who argues that technology will always be subject to limitations and biases. In fact, Coyne contends that the closer we get to technologies, the more pronounced their limitations. If this is the case then our central subject of digital fabrication – through its affordances – has the ability to destabilize current habits and spaces.

Consumption

Although digital fabrication techniques have their origins in engineering and high-value manufacturing, I will be dwelling on the recent do-it-yourself (DIY) digital fabrication movement and the attention recently given to consumer 3D printing by 'big business.'

By 2008, two names had become synonymous with 3D printing: MakerBot and RepRap. The MakerBot was a relatively refined 'flat-pack' kit that could be purchased online, while RepRap came to media attention because of its ability to replicate itself; it was possible to print key parts on one RepRap for the construction of another, then purchase additional components over the counter at hardware and hobbyist electronic stores. In 2010, I attempted a RepRap build with a group of students as part of a 12-week course at the University of Auckland. This experience revealed that while a novice could construct as much as 80% of the RepRap, considerable specialist knowledge was needed to build the remaining critical 20%. For example, key tolerances had to be achieved by tuning nuts and manually measuring dimensions on treaded steel bars. In addition, the thermistor, which controls the temperature of the printing nozzle, required considerable specialist electronics knowledge for assembly. With the assistance of one of the developers of the RepRap project, the 3D printer was assembled at the end of week 12. However, while the attraction of the machine was to facilitate experimentation with material prototyping, instead the entire course was spent deepening understanding of the materials of construction, and building and fine-tuning the 3D printer (Figure 2).

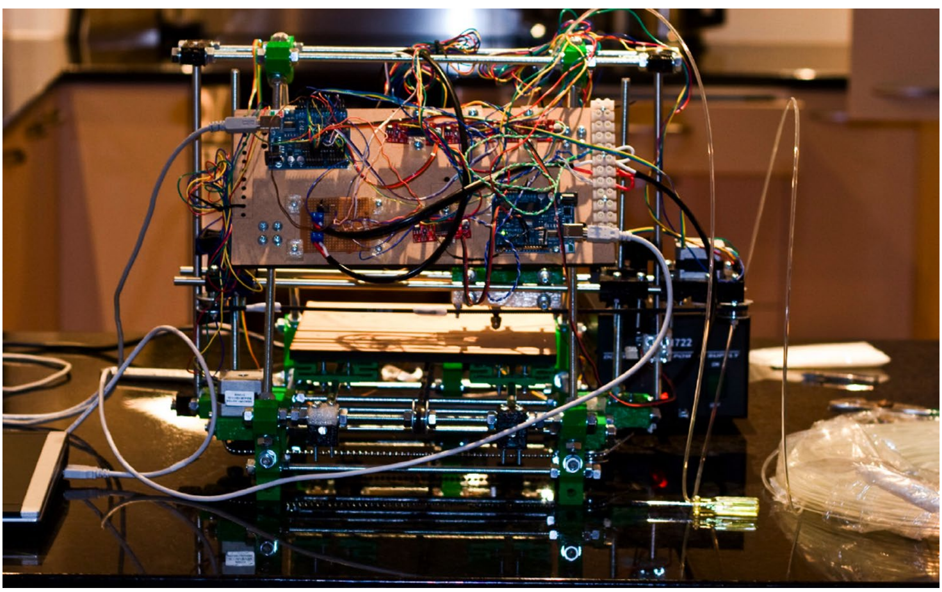

Figure 2. RepRap assembled in 2010 by J. Guest, D. Wong, M. Bayly (image by author).

With so much time being invested in assembly and tuning, there was little time for experimentation. Although a large amount of material understanding was gained through the building of the RepRap, it was never utilized within a design process. Later, in 2012, another build was attempted, this time an Ultimaker 3D printer. The printer was assembled in the course of a few weeks and was working perfectly immediately upon completion. Advances in the culture of DIY and buildability meant that, in this case, it was built by a teenager. The ease of assembly, by a 'flat-pack' methodology of highly accurately laser-cut parts and a better understanding of the need to preassemble items requiring specialist knowledge, resulted in this printer being quickly assembled and used in a design course. Currently, a wide variety of desktop fabrication appliances are available. As well as 3D printers, there are computer numerical controlled (C.N.C.) routers and laser cutters, all available and marketed as easy to use by anyone. The material knowledge of the machine assembly is now largely irrelevant. However, as I will discuss next, material knowledge continues to be important in utilizing the machine for making.

Although useability of 3D printers and other desktop fabrication appliances has significantly improved, material knowledge remains important. Certain geometries and tolerances are not achievable, at least not without some understanding of both the properties of the material and the tool. For example, a particular object may print better if turned on its side or upside down. There are also a variety of 3D printer types that use plastic filament, powder or a liquid resin. Each type of tool has different properties and makes objects differently. Consequently, some shapes and details work better on some types of 3D printer than on others; success is reliant on a knowledge of the tools and the material. For now, these devices are also relatively slow compared to commercial manufacturing tools. They have, however, become popular within various design disciplines. Historically, for physical models to be of value within a creative process they were quickly produced, and consequently they were abstractions and limited in detail. Alternatively, a highly detailed model might be created towards the end of the design process, the intention here being communication of the design to laypeople. With the widespread proliferation of 3D printers, scaled models can – concurrently – be created quickly and with a high level of detail and complexity, still rendering them usable within design discourse. This provides a richer rendering of space or texture and, as a consequence, a designer's reading of light, architectonics and spatial grammar is heightened. It is altering what Snodgrass and Coyne (1997) would contend is design as hermeneutic cycle; it is changing the means by which we describe, understand and make our world.

Turning to the high street, since 2011 we have seen interest from big businesses such as ASDA and Staples to capitalize on digital fabrication, particularly 3D printing. Print-on-demand and ebooks were reshaping the literature sector of the consumer market at this time, and it was believed that 3D printers would create new market opportunities and business models. However, I have unpacked digital fabrication elsewhere and suggested that materiality continues to have value within the making process (McMeel and Amor 2013). This presents a challenge for big business; super- and hypermarkets are highly sophisticated spaces entangled with processes of consumption. They locate shoppers within a narrative of carefully positioned items to encourage impulse and other forms of purchase. We do not engage materially, in any meaningful way, with objects in a supermarket, so what happens with 3D printers – where materiality appears to be significant – when placed within these frameworks?

To date, these devices seem to have been slotted into spaces, not unlike the print-on-demand photo services, and offerings in ASDA, according to the *Guardian Newspaper* are limited to printing a 'mini me' (Gibbs 2013). They appear limited to exploiting the novelty of printing oneself or, as per Staples in the U.S., creating an online store to sell print-on-demand products. In this regard, it is an extension of the photography 'on-demand' mode of consumption, which continues to obfuscate the material practices and emerging manufacturing possibilities of these machines. What is significant is commercial retailers' removal of material engagement to fit these devices into their existing consumer framework. To deepen our understanding of the social and material affects, we will turn our attention to design practice that uses digital fabrication – in the extreme – to gain insights into the knowledge practices that are developing with these technologies, and explore what relevance they may have.

Digital fabrication

This section offers a deeper and prolonged analysis of digital fabrication within the more extreme context of design. Drawing on my own practical research, it will scrutinize the tools of design, representation and manufacturing used to make several objects: a table, chair, robot and scaled model of a building. Of interest here are the social and knowledge practices surrounding design and manufacture. It is perhaps useful at this point to distinguish between two important processes: first, the encoding of digital goods for *transfer to manufacturing people,* and second, the encoding of digital goods for *transfer to manufacturing tools*.

The complexities of communication in design and construction have been documented elsewhere, including investigations into technologies such as phones and augmented reality (McMeel and Amor 2011a; McMeel and Amor 2011b; McMeel, Coyne, and Lee 2005). What is of specific interest here is how, within the field of design and construction, drawings persist as the primary means of communication. The traditional construction drawing is an example of what I call encoding digital goods for *transfer to manufacturing people,* wherein drawings are abstracted from highly detailed and accurate 3D digital building information models (B.I.M.). While a model contains detailed material, specification and furniture information, drawings remain a limited abstraction of this digital representation. Yet they continue to be the most popular means for transferring knowledge between groups of people for manufacturing and construction.

By contrast, the table illustrated in Figure 3 is an example of encoding digital goods for *transfer to manufacturing tools*, sometimes referred to as direct digital manufacturing. People are complicit in both instances of encoding; however, a drawing represents the encoding of information for transfer to a person who will invariably interpret it. Figure 3 illustrates processes in which people do not interpret the information encoded in a digital file. Instead, they ensure it can be processed safely by a manufacturing tool, and then execute particular processes to ensure it is manufactured as intended. The change in materiality of the data being transferred by these two methods has brought about a change in the social, material and knowledge practices of the design and fabrication team, which I will discuss throughout this section.

Digitally encoding the 'soft' table

The table illustrated in Figure 3 is heavily influenced by the work of artist Salvador Dalí; the table is intended to evoke the feeling of being melted. Sketched manually over a period of

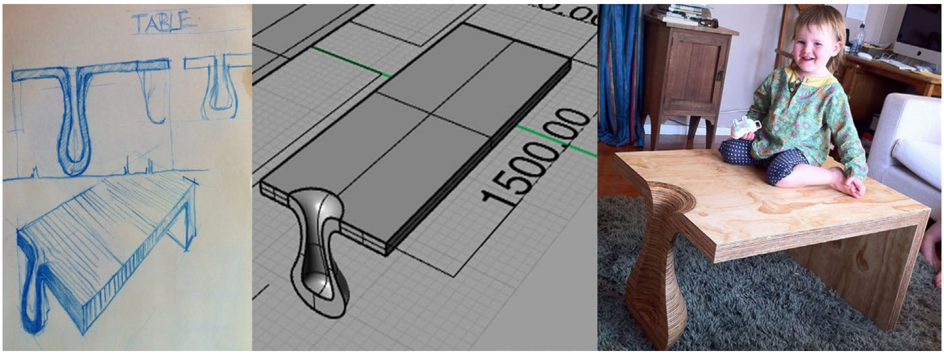

Figure 3. Left: The 'soft table' sketch. Middle: 3D model rendered in Rhino. Right: Finished table.

days, the specific geometry was digitally modeled using the Rhino modeling software. Renderings (illustrated in Figure 3) were used to prompt discussion between traditional and digital manufacturing specialists to assess how the table could conceivably be manufactured. Eventually, it was agreed that the best course of action was to separately manufacture the 'soft' leg and tabletop via C.N.C. routing, and then assemble the two parts with a traditional 'biscuit' technique.

A number of manufacturing challenges revealed themselves as we began collaborating; this led to prototyping the leg in polystyrene, which confirmed two problems. First, where the leg geometry tapered exponentially to zero, the polystyrene was splintering erratically. A consequence of the geometric properties of the model, this splintering would recur on a variety of material prototypes. Second, the curve of the leg resulted in the collet (or chuck) that holds the cutting tool of the router to collide with and damage the leg during manufacturing. The first problem was resolved by changing the location at which the tabletop and leg joined – this removed the exponential geometric tapering from the leg piece. The second problem was resolved by subtly altering the geometry of the leg. These changes produced no noticeable difference to the appearance of the table. The amended digital file was the only documentation passed to the digital fabrication specialist for manufacturing. The rectangular plywood blocks from which the items would be milled were prepared in the traditional workshop and then transferred to the digital fabrication workshop for shaping. The finished pieces were later returned to the traditional workshop for joining, sanding and finishing; a detailed video of the process can be found here: https://vimeo.com/35361578. I would like to draw attention to two instances within this process that shed light on how the introduction of a new tool – a C.N.C. router – impacted knowledge practices.

In the first instance, having completed the initial routing on both pieces, they were turned upside down for further shaping on their underside. The digital fabrication specialist noticed that the initial routing cuts were approximately 20 mm from the center of the table. It had been assumed by the specialist that the leg was centered on the table, and it was only realized when routing was underway that this was not the case; the position of the table leg was, in reality, not known by the specialist before manufacturing began. However, when we encode for transfer to manufacturing tools, the requirement for explicit and detailed geometric knowledge of the object by the fabricator can be significantly reduced. This is due to the specifics of the geometry being encoded within the digital file, and the digital fabrication specialist using the file to apply correct manufacturing processes to the material. Thus, when the router was initiated it moved to the correct position and began cutting accurately.

The second instance that is of interest pertains to explaining the disparity between the length of the table in the rendering and the final product, as illustrated in Figure 3. The dimension 1500 was handwritten on a paper drawing that was passed to the traditional workshop. This workshop would prepare two blocks of wood of specific dimensions from which the leg and tabletop would be milled on the C.N.C. router. Due to the penmanship, the '1' was mistaken for a '7;' thus, the dimension 1500 mm was interpreted as 750.0 mm. What is of interest within the context of this discussion – and which we will scrutinize in the following section – is how the imperceptible 20 mm offset of the leg was carried through to the finished product without ever being known by any of the manufacturing stakeholders in either the traditional or digital workshops. Yet the length of the table – something that was communicated seemingly clearly through traditional drawing annotation – was lost in translation.

Reflections on direct digital manufacture

Design descriptions traditionally take the form of plans, sections and elevations; i.e. Cartesian geometry used to record information for transfer between groups and people. Although there are notable exceptions at the cutting edge of design and construction (Burry, Burry, and Davis 2011; Kolarevic 2003; Kolarevic and Klinger 2008), this is generally still the case. Even where sophisticated B.I.M.s are employed, they are eventually abstracted to a drawn schematic for manufacturing and construction purposes. Yet in our example, it was the manual drawing that was misunderstood and the digital encoding of the table that reliably carried the nuances from the design through to manufacture. If we are finding better ways to translate goods between design and manufacturing, why does the drawing remain so pervasive?

It is easy to overlook how harsh the construction environment is and how robust and resilient traditional drawings and communication processes need to be to operate successfully within that environment. The drawing is also culturally privileged within design and construction. Vitruvius, in the first chapter of book one of *The ten books on architecture*, states 'let him be educated, skillful with the pencil, instructed in geometry' (Pollio and Morgan 1960, 5), establishing the importance of drawings and Cartesian geometry in, arguably, European civilization's first design manual. There is also the story of Giotto, the Italian painter and architect who displayed his skills to Pope Boniface the Eighth by drawing a perfect circle and thus securing the commission to paint St Peter's Basilica (Land 2005). The suggestion that drawing ability is a direct metric for measuring skill or craftsmanship is deeply embedded in creative culture. In our table example, drawings were not used for the transfer of information for manufacturing, although they were used extensively during the more discursive social and knowledge processes that we associate with the early design stages. Material practices that usually happen as design gives way to construction also had to occur much earlier. These observations support the hypothesis that the value of drawings is decreasing, at least as a means to transfer information in the form of Cartesian geometry. However, it also reveals that they continue to have importance in helping different stakeholders converge on mutual understanding.

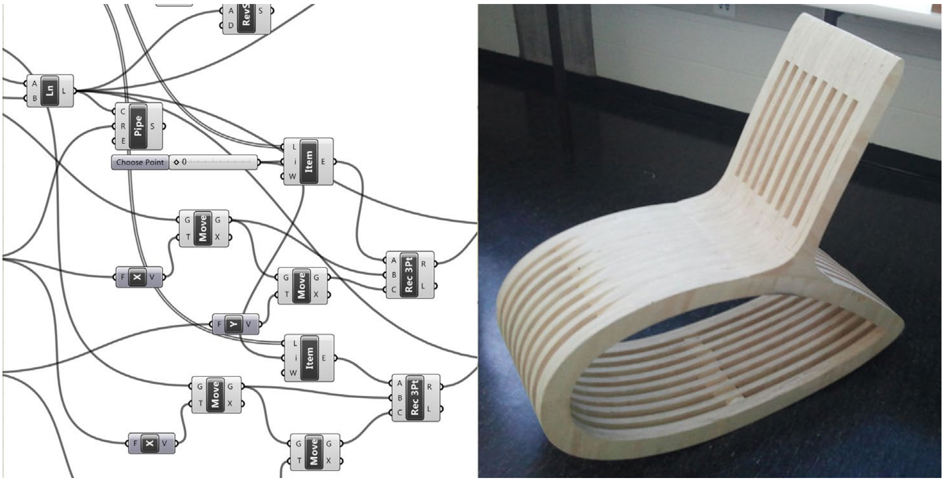

Figure 4. Parametric description and manufactured rocking chair by L. Ea.

A follow-up design studio in the School of Architecture and Planning introduced parametric tools into this digitally sponsored fabrication process to explore further aspects of digital materiality. Observational evidence from the studio, perhaps best reflected in the 'Rocking Revival' project (Figure 4), also supports the thesis that drawings are being challenged as the primary means of transferring knowledge for manufacturing. In this example, the parametric description of the chair allows the designer to alter the height and width of the seat. The parametric design description automatically slices the digital model of the chair into sections, which can be easily exported as Cartesian vectors for direct processing and cutting by a C.N.C. router for manufacture. If the designer changes the chair parameters, the parametric description will automatically change relational parts to the appropriate size and update the Cartesian vectors. Thus, knowing the specific dimensions and geometry of the individual parts of the chair becomes redundant. The etymological origins of 'parametric' are perhaps telling: para, 'contrary to;' and metric, 'that means by which anything is measured.' Parametric ideologically challenges the Cartesian dogma that underpins much of design and making; a challenge that may have it merits, as a deeper reading of Vitruvius reveals blind faith in numeric measurement may be misguided. McEwen draws our attention to the use of *tempering* – meaning to soften or mitigate – by Vitruvius within his rules for design (McEwen 2003, 198). The point Vitruvius makes is that the appearance of symmetry is more desirable than numeric symmetry. Here, in this founding design and construction manual, Vitruvius is perhaps acknowledging measurement as suboptimal for encoding design intent.

A shifting foundation of knowledge practice

Parametric materiality and digitally sponsored fabrication processes are altering, in particular, reliance on Cartesian measurement. Mark Burry analyzed parametric encoding in relation to understanding (Burry, Burry, and Davis 2011), and suggests that parametric schema can be used to improve design legibility. This is of particular interest to Burry within the context of utilizing highly complex parametric schema in a collaborative and specialized environment. The research documented in this paper points to parametric schema offering the ability to deeply encode the designer's intent and potentially reduce or eliminate the loss of important, albeit esoteric, choices made during the design process. Research surrounding digital materiality cannot be confined to matters of representation and geometry; it has consequences for both social processes and knowledge practices surrounding communication and documentation. The shift from drawn to digital materiality is not incidental in this discourse; it is a major change within the foundational cultural practices of how we make our world. It changes the social and knowledge practices that surround and permeate design and construction processes.

Directly manufacturing robots

We now turn our attention to a selection of design projects employing 3D printing. Where our observations have led us to revisit Leví-Strauss' seminal text *The savage mind* (1966), and reflect on the relationship between materiality and ways of thinking.

On the master's program at the School of Architecture and Planning within the University of Auckland, a student aimed to develop a novel robot for fabrication. Initially, two DIY robot kits were downloaded from a website; a KUKA-style automotive armature robot and a delta robot. Both kits came with parts encoded in 2D vector files, which could be laser cut and assembled. The delta robot is of particular interest within the context of this paper, as a 3D printer was employed to make a series of complex ball-joint assemblies.

The ball joints, as highlighted in Figure 5, allow freedom of movement in all three axes and are a key part of the design and operation of the delta robot. A standard commercial brass joint was relatively expensive and heavy, putting the small servomotors under stress and affecting movement of the robot. The student opted instead to print these joints on a high-quality nylon 3D printer. The resultant assemblies highlighted in Figure 5 were strong, light and with a relatively low friction coefficient that allowed smooth movement. Eventually,

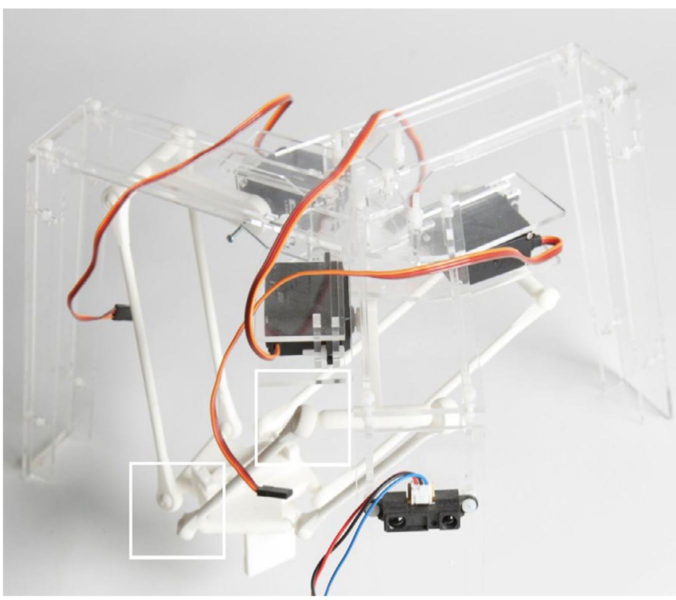

Figure 5. Delta robot with highlighted 3D printed ball-joints (A. Kumar).

a large percentage of the delta robot, including the armatures and end effector, were designed and 3D printed as a single assembly. It was a highly cost-effective process and the materiality was adequate to function structurally on a project of this scale. Redesigning and rethinking was now transformed, as all parts and the manufacturing possibilities were essentially under a state of contingency and could be radically changed if necessary.

Bricolage or engineering?

We couch our observations in terms of bricolage, which is one of two methodologies for problem solving established by Lévi-Strauss in his seminal text *The savage mind*. The other method – to engineer – refers to designing a unique solution to a specific problem. The engineer requires mastery of a specific domain and materials in order that they might conceive of and deploy tailored solutions to individual problems. The bricoleur, by contrast, requires no such mastery; a bricoleur is in possession of a kit of parts, so to speak, appropriated from specific contexts. The parts have been appropriated because of their propensity for reuse and recombination, helping the bricoleur to address problems. The difference – Lévi-Strauss contends – is not in the complexity or sophistication of the problem that the bricoleur or engineer can address, but rather in the methodology of problem solving. If we are to say that the engineer designs a solution, then the bricoleur divines theirs through bricolage, critique and iteration.

Leví-Strauss' decision to exemplify his observations in terms of *engineer* and *bricoleur*, rather than engineering and bricolage *processes*, suggests that they are mutually exclusive cognitive processes – ways of thinking engrained in the individual – not simply problem-solving methods to be chosen as and when needed. Yet that is precisely what was observed during the design and construction of the robot. In the early stages of the robot project, it was bricolage that dominated; in the later stages of the build, particularly during decision-making surrounding the ball-joints, we saw engineering take center stage. The student, now with considerable knowledge, as well as access to a 3D printer and its assorted techniques, began to engineer bespoke components addressing specific problems and contexts. When questioned on the implications of having access to a 3D printer, the student found it hard to elucidate his design process and the implications of the technology. It appeared that his entire creative processes were put into a state of contingency, as the potential existed to redesign and print any components within the robot.

In a parallel project, a 3D printer was used by different students to create a scaled model of an unconventional skyscraper design inspired by human bones (Figure 6). The students initially used online and freely available tutorials, code and models to understand bone shapes and growth patterns. As their knowledge grew, they began creating their own 3D objects for printing, although it took time to grasp the materiality and digital requirements to build and save digital objects for 3D printing. What is of interest here is that both the robot and unconventional skyscraper projects quickly moved from downloading objects and bricolage to the creation, the engineering, of unique objects.

Scaffolding for problem solving

Rather than methods for problem solving being deeply ingrained in cognitive process, our observations suggest that the tools at our disposal inform them. Both projects displayed

Figure 6. 3 D printed digitally sponsored designs (B. Hume, W. Kobus).

elements of bricolage, appropriating code and toolkits at the early stages to assemble projects much faster than would otherwise be possible. However, when given access to 3D printing technology, bricolage was employed as part of a cognitive process that also included the careful engineering of bespoke components and designs. The technology operated much like a cognitive scaffold, a theory advanced by Clark (2001) which argues that the physical environment informs our thought processes. Thus, digital fabrication does not just provide novel methods for fabrication; it is creating new tools that support different ways of thinking.

Conclusions

In sum, this paper addressed digital fabrication in relation to materiality in three ways. First, it traced a historical narrative of habit and habitat to bring materiality to center stage, highlighting not only the entanglement between space and design technology, but also that the social and organizational processes that unfold within those spaces are subject to influence. Retailers are inserting these devices into existing consumer models of consumption, removing materiality completely from the interactions and discourse that surrounds them. This removes any possibility of encouraging the new knowledge practices observed as emerging in the design research examples outlined above. It is perhaps both telling and encouraging that these commercial endeavors have expanded little beyond the novelty of printing oneself. In opposition to this, *makerspaces* represent an evolving spatial typology to support digitally sponsored design and fabrication, serving to illustrate how material practice is complicit in spatial and design practice. Second, by unpacking design processes we see how social practices change. The clear decline in the use of drawings as a means to contain and transfer Cartesian geometry signals a major change in foundational knowledge practices within design and construction. Drawings were by no means redundant in the processes studied here – they helped to stimulate discourse and align understanding between different stakeholders. Not overlooking valuable research into systems and process modeling, this, however, highlights the fundamentally human experience of technology. It sponsors social interactions and changes knowledge practices within the design and making process. Third, by scrutinizing a selection of projects that utilized 3D printing, the observational evidence suggests that they promote new knowledge practices and ways of thinking. It is encouraging – within the context of digital design and fabrication – that bricolage and appropriation of pre-made objects serves only as a precursor to the bespoke design and engineering of unique solutions. There is more happening here than the often-cited Marxist position that technology deskills and does not favor the individual. Studying the changing social, knowledge and spatial practices that surround digital descriptions and new methods of fabrication is hoped to set the stage for future research that demotes the fascination with geometric form in lieu of intensifying the critique and analysis of materiality within the social and knowledge practices of digital design and making.

Notes on contributor

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