Collaborative Making in Craft and Virtual Reality

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Abstract

This paper examines a collaborative practice of an analogue and a digital craft practitioner developed at Emily Carr University of Art + Design in Canada. Its aim is to illuminate ways in which craft making and hand-crafted objects can be translated using 3D modeling technology and addresses the following questions: (a) What forms of knowing and meaning making are evolving through collaborative practice? How does this inform research creation at an Art + Design University?; (b) What does it mean to manipulate material in Computer Aided Design (CAD) through Virtual Reality (VR)? What are the explicit implications of doing so and how does this inform analogue material practice and experimentation?; and (c) What are the pedagogical implications of this mixed analogue/digital workflow and practice? Originating with a hand-knotted object, the study began with the transformation of this analogue form into digital form using a range of techniques. These activities act as both a survey of digital fabrication capabilities and a way of exploring new thinking mechanisms offered by this emerging form of practice. The study seeks to broaden our understanding of the maker's role within the capabilities and limitations of digital interface and fabrication. Throughout this collaborative practice, each iteration of digitally-fabricated objects was documented and reflection was made on both the outcomes and the ways in which the analogue and the digital craft practitioners work together. This emerging collaborative practice acts as a catalyst for established disciplines within art and design to collide and interact. Outcomes of this study include mapping new workflows within digital/analogue material practice, and reflection on how the materials and methods used in digital fabrication have the potential to expand the meanings connected to the things that are produced. The study also reveals a few provocations impacting the uptake of CAD and 3D modeling skills in the classroom, through collaborative, interdisciplinary practice.

Theme: Actors
Keywords: CAD, collaborative practice, digital fabrication, new craft, virtual reality

1. Introduction: CAD and digital manufacture in craft practice

Technology and "machine culture" have a close association with ideas of precision, reproducibility, and certainty; CAD environments generally reinforce these qualities because their platforms have often been developed for industrial design and mechanized output. The promise of direct digital manufacture has reintroduced questions about the role of the hand in mechanized production. Ruskin's spirit has re-emerged. The conversation has matured since Sennett's (2008) observations that:

> As machine culture matured, the craftsman in the nineteenth century appeared ever less a mediator and ever more an enemy of the machine. Now, against the rigorous perfection of the machine, the craftsman became an emblem of human individuality, this emblem composed concretely by the positive value placed on variations, flaws, and irregularities in handwork. (p. 84)

Writing in different times, Sennett and Ruskin offer up similar perspectives on handwork. They advocate for handwork as a necessary means of production but also note its demise due to automation, its shift in location and connection to personal identity and political outlook. Craft practices using traditional materials and handwork often emphasize experimentation and discovery over output and production. The ideas that arise through use of materials and processes are one of craft's great assets. They serve to augment and are as valuable as the intentions each practitioner brings to a project. Craft practitioners' sapient and adept manipulation of materials is an excellent entry point and a potent means for reconsidering digital manufacturing frameworks. Here the relationship with an artefact is understood as a continuous ongoing set of relations. Translated to rendering a model in CAD, the hand and the digital tool, be it a mouse, a stylus, or other, are implicit to the outcome. The conundrum to this, as pointed out by Nitsche, Zwaan, Quitmeyer, Nam, and Farina (2014, p. 720), is that "Craft requires proximity and skill with physical materials, whilst the digital inaugurates a completely new spatial logic."

While digital fabrication and open source tutorials on 3D modeling have transformed the practice of some designer-makers, other skilled craft practitioners seeking direct interaction with materials through handwork do not see digital interfaces as affording supportive arenas for their creativity. This paper aims to illuminate ways in which craft making and hand-crafted objects can be translated using 3D modeling and virtual-reality technology through collaborative practice, addressing the following questions:

- What forms of knowing and meaning making are evolving through collaborative practice? How does this inform research creation at an Art + Design University?
- What does it mean to manipulate material in Computer Aided Design (CAD) through Virtual Reality (VR)? What are the explicit implications of doing so and how does this inform analogue material practice and experimentation?
- What are the pedagogical implications of this mixed analogue/digital workflow and practice?

The collaboration exemplified in this paper took place at Emily Carr University of Art + Design over the course of 2.5 months, between Nithikul Nimkulrat in her role as Designer in Residence, and Aaron Oussoren in his role as Affiliated Researcher with the University's Material Matters Research Centre. Each collaborator brought different skills to the project. Nimkulrat has worked extensively in textiles; her practice mixes experimental and traditional forms of knotting to produce evocative art installations. Oussoren works fluently in CAD and 3D printing processes, and applies this to an expansive understanding of glassworking methods as well as mould making for ceramics. These varied skill sets provided some tools and starting points to develop and expand upon the use of digital manufacturing methods related to traditional materials. The following sections will examine a collaborative project using digital tools to evolve a form through paper string, knots, 3D scanning, CAD, Virtual Reality, and 3D printing. Reflection on this collaboration is expected to shed light on how shared interdisciplinary making can contribute to the development of individual collaborator's methods of making and subsequent creative output.

2. Hand crafting through 3D scanning and CAD modelling

Intent on understanding digital processes through a craft lens, Nimkulrat used her long-standing craft knot technique to construct a small artefact for further experimentation with digital tools available in the Mixed Reality and Digital Fabrication research labs at the University. The hand-knotted object was made in the form of a coffee cup and saucer (Figure 1), a replica of *The Coffee Cup* in Nimkulrat's installation *Paper World* (2007) (Figure 2) connected to her practice-led doctoral research *Paperness* (Nimkulrat, 2009). The new form transforms and moves from analogue to digital form using a range of techniques.

Nimkulrat and Oussoren first 3D-scanned the knotted artefact using a high definition Polhemus 3D laser scanner. They envisaged this as a means to translate the analogue artefact into a digital format suitable for manipulation in CAD and 3D fabrication in the labs (Figure 3). The first

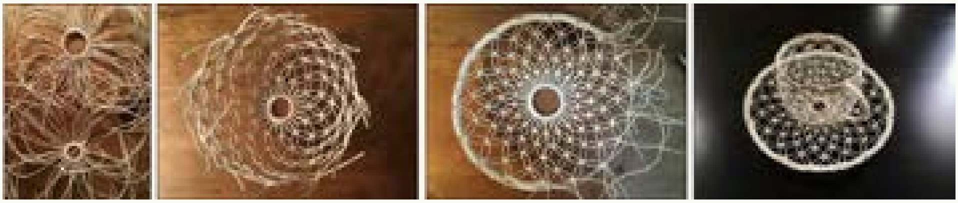

Figure 1. Process: the making of the coffee cup and saucer.

Figure 2. The Coffee Cup in the Paper World (2007) installation.

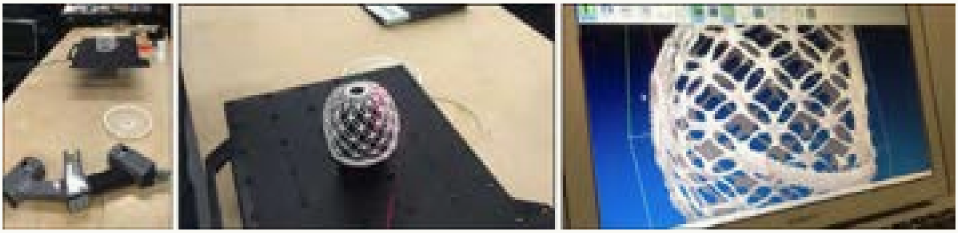

Figure 3. Polhemus Scorpion handheld 3d laser scanner; the scanning process; and the 3D scan.

scanning attempt was carried out with reservation. Curiosity as to how well the intricate details of the knot structure and 0.8mm-diameter paper string could be captured drove the process. Scanning required the movement of the hand in coordination with the eye focusing on the rows and columns of knots. Scans of the cup, although missing details, showed a line quality that resembled the characteristic of paper string and the "handmade." The generated scanned files, however, were too large to process effectively in CAD and crashed both the University's and the hardware manufacturer's computers. The incompatibility between the craft object and the technology were revealed; the properties and characteristics of the craft object were beyond the capacity of the digital tools.

The next approach involved freehand drawing on a photograph of the hand-knotted cup. Using this method a simplified model was produced that avoided the complexity and unmanageable amount of data generated by the previous high-resolution laser 3D scan. A photograph, serving as a template, was imported into the CAD software. This image was then displayed on a WACOM tablet and traced with a stylus (Figure 4). Handling a digital tool to interact with the CAD program resonates with Malafouris's (2013) "Extended Mind" hypothesis. In this case, the mind extends to the virtual software and the body (hand) to the digital tool and machine. One section of the knotted pattern was constructed.

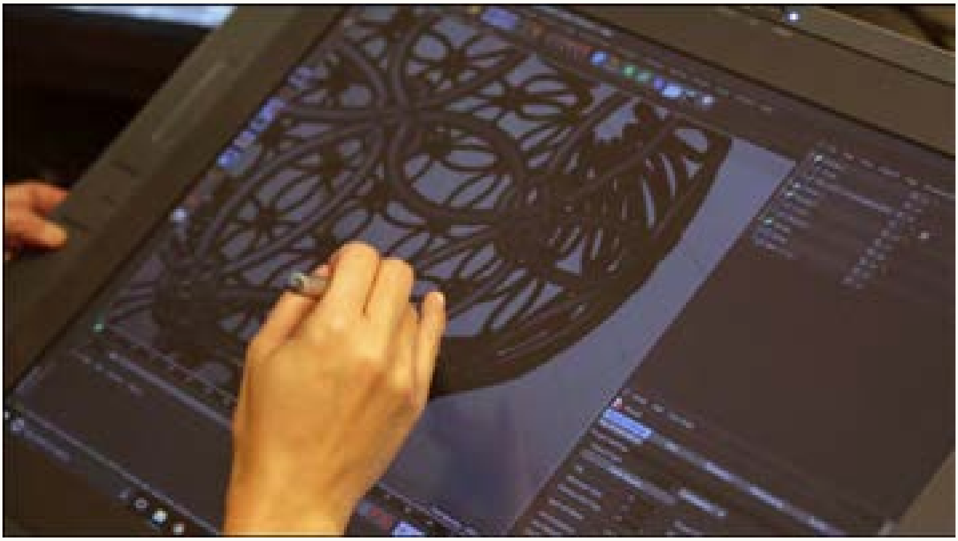

Figure 4. Working on WACOM tablet using a stylus.

A three-dimensional array of this pattern allowed the collaborators to achieve a likeness of the original knotted cup (Figure 5). The resulting watertight model (Figure 6) was suitable for use on a variety of output platforms including 3D printing in plastic filament and plastic composites, and 3D printing in plaster for the moulding of slip-cast porcelain. It is worth noting that throughout the process of developing the CAD model of the cup, communication between Nimkulrat and Oussoren was key. Experts in their respective fields but having limited skills and knowledge in each other's domain, they had to continually find ways to understand intention and speculate on next steps in the process, e.g., through a demo, drawing, etc.

The translation of the knotted form into digital model presented an opportunity to explore the limits of laser 3D scanning and creatively explore CAD modelling. Out of necessity, the starting material, string, needed to be worked with according to prescribed material parameters and capabilities – things that string does well (flex, self-friction, knot, bend). In a similar sense, the digital model was developed according to the parameters of the CAD software. Objects produced in CAD have been described as being trapped in a predetermined visual language, based on things that CAD does well, like skew, duplicate, scale, rotate. The work, to this point, was a record of material manipulation according to analogue parameters, translated into a prescriptive CAD language. The collaborators began to ask: Can the idea of responding to the limitations of a material, to loose threads, cracks, and stiff knots, translate into virtual space? The next section describes the 3D printing process and the resulting prints of the CAD model in Figure 6.

Figure 5. Tracing the knot structure with a stylus and a section of knots imported to Cinema 4D for generating a three-dimensional array of this knot pattern, forming a likeness of the original knotted cup.

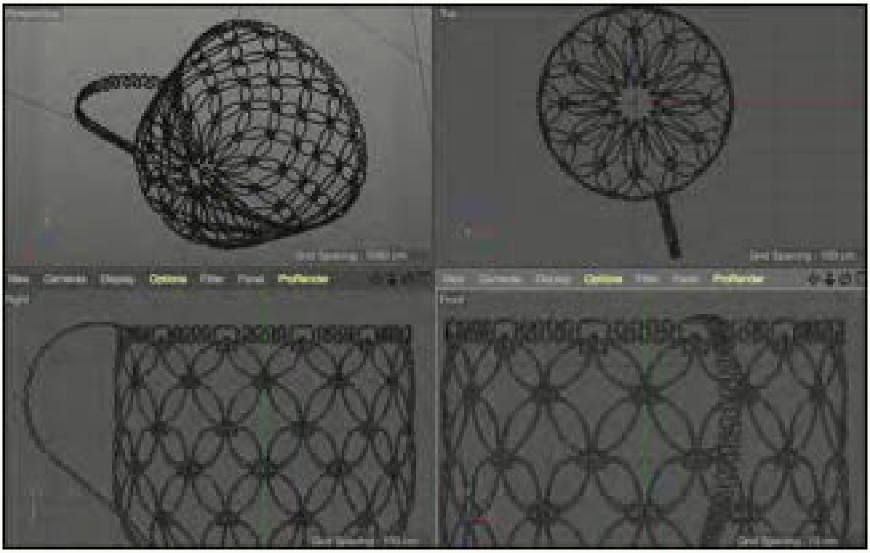

Figure 6. The resulting 3D model of the cup.

3. 3D Printing with filament: Uncertainty and imprecision of digital fabrication

Material manipulation in virtual space opens up the opportunity to deepen our understanding of the potential expression and poetics of mixed analogue/digital production. Seelig (1992/2009) describes this experimental dialogue with materials as central to a creative practice, saying:

> To make form that responds only to a material's physical properties – to what it can do rather than [what] it encourages us to do – more often produces results that are predictable and familiar. The artist's ability to discover qualities in materials that go beyond their scientific properties will provoke form with a far more convincing sense of expression. ... Materials contain clues that allow usto discover our own personal sense of reality through a subconscious process, an intuitive, creative process in which material is an active partner. (p. 55)

Seelig's (1992/2009) conception of responding to materials in terms of "what they encourage us to do" and consideration of material as an "active partner" seems well suited to both crafting a physical object by hand and working with digital content. The development of the model in CAD had required many hours navigating the restrictions of the software to achieve a model suitable for output. The translation of the knotted cup to CAD models illustrated the parameters of the analogue and virtual materials; the team's next translation from virtual model to 3D print would allow for a new response to the original object, returning us to an experience of material as an "active partner" in a more familiar, tactile form.

As Nimkulrat had not worked often in digital output, she assumed that the transformation of a CAD model to 3D printed form would be straightforward, and that digital fabrication should have a certain level of precision and certainty. This was not the case. 3D printing the virtual cup model presented challenges due to limitations of both print materials and printers, similar to those of craft materials and tools according to task. On encountering the uncertainty and imprecision of 3D printing, Nimkulrat wrote in her journal: "Digital fabrication is not accurate as it may seem. This probably is due to the fact that no judgement of the maker is being constantly made in process (unless the maker observes the machine absolutely at all time" (Nimkulrat, personal note, November 7, 2017).

Nimkulrat and Oussoren explored 3D printing on a range of technologies and scales, including thermoset and thermoplastic material production systems like the Stratasys Objet30, a large format Stratasys F370, and finally a desktop Tinkerine DittoPro 3D printer. At this stage, details of the model were set to be printed as small as 0.4mm using only partial support material as a means of testing and understanding the limitations of the Tinkerine printer. PLA (a thermoplastic) filament was used. The printer managed to print the entire CAD model, but the physical print was too fragile to retain the cup form (Figure 7). This first print that provided the researchers evidence of the capabilities of the printer also inspired students working in the Digital Fabrication lab. Observing Nimkulrat and Oussoren's progress they began to develop their own CAD work in finer detail, thereby further exploiting the full capabilities of the machine.

Based on the print described above (see Figure 7), the 3D CAD model was modified. Gradual increases of the model thickness were tested by printing replicas of varied thicknesses: 0.8mm, 0.95mm, and 1.2mm (Figure 8). In this way the "right" thickness, suitable to the capacity of the machine that also preserved the characteristics of knots, likeness of strings, and fidelity of hand-knotting, was determined. Having compared the resulting prints in different thicknesses, the collaborators agreed that the 0.95mm test print was the most successful. Based on this further 3D

Figure 7. The first 3D printing of the cup on Tinkerine DittoPro 3D printer.

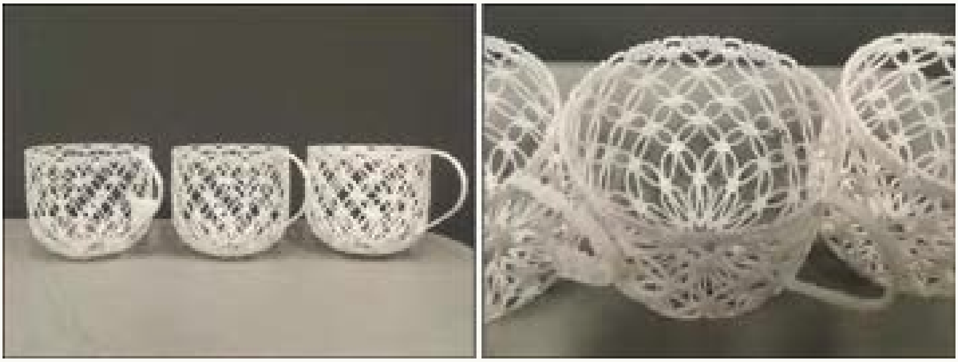

Figure 8. Printed cups in three different thicknesses: 0.8mm, 0.95mm, and 1.2mm.

printing was conducted using PLA composite materials, including wood (30% wood, 70% PLA) and copper (30% copper, 70% PLA).

A solution for successful printing with the selected composites had to be sought through experimentation with adjusting different parameters of the printer's slicing software, such as temperature, speed, density, angle of support material, and many others. For example, the wood filament proved to be extremely fibrous, and clogged the extruder nozzle easily. In response to this the speed was increased by 10% to achieve a better flow of filament. Despite the revised material parameter settings, the resulting prints were still missing parts. The CAD model was re-adjusted and modified again, increasing the wall thickness to 1mm. After several iterations of parameter settings and printing, the researchers were satisfied with the outcomes. Printing the same model with different materials generated interesting results. A close comparison of the printed

Figure 9. 3D printed cup using three different materials: (from left) PLA, copper, and wood.

cups made it apparent that each filament offered a distinct set of material features (Figure 9). The fibrous effect of the wood print looked similar to growth of roots and was considerably lighter than the ones printed using copper and PLA composite filament.

4. Crafting in virtual reality

The above sections have outlined and characterized the transformation of a hand-crafted object into a CAD model printable on a 3D printer into digitally-fabricated objects. The printed cups had their own characteristics as expressed by the material used; their appearance was generally comparable to the original cup. What was missing from the printed cups was the continuity, flexibility, and bendability of knots, or things that string does well. For this reason, an attempt to represent the nature of knots was made. In parallel to the exploration of printing the cup model with different composites aforementioned, the researchers created a new CAD model of flexible, loose knots. A stylus was employed again to create a section of knot pattern for further 3D modelling. Although Nimkulrat has hand-knotted her three-dimensional work for a decade, virtually knotting on a 2D screen was incomprehensible. The use of a flat screen to work on a 3D model did not adequately depict or open up access to creating a real-world, three-dimensional object. The positions and the interlacing of strands that construct knots were difficult. Although he had no prior experience in himself, Oussoren suggested that drawing in virtual

Figure 10. Drawing of a section of knots, crafting knots in VR, and CAD Model of a section of flexible knots.

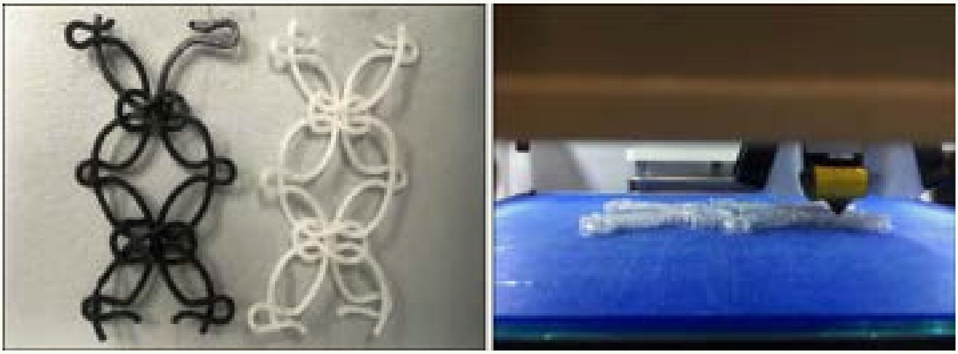

Figure 11. Comparison knots prints from different printers and a side view of the print process showing support material.

reality (VR) space might help resolve this barrier. With the assistance of researcher Sean Arden in the University's Mixed Reality Lab, Nimkulrat was able to draw knot structures in a 3D VR space in a similar (though scaled up) gestural manner to real-world hand-knotting of string. The initial VR drawing session enhanced Nimkulrat's understanding of the three-dimensional positions of strands of knots. Although the drawing in VR was not directly imported to the CAD program, the experience helped to make a CAD model of a section of knots (Figure 10).

Having found a solution for the making of a CAD model through the use of VR, the next solution was to solve the 3D printing process. Often when the model was being printed, the printing nozzle would irritate on a previously printed area with a steep angle and would subsequently shift from its original position on the support material forcing the next printed layer to detach. Initial print iterations fell apart when the support material was removed, or, if they managed to stay whole, had a cracked,

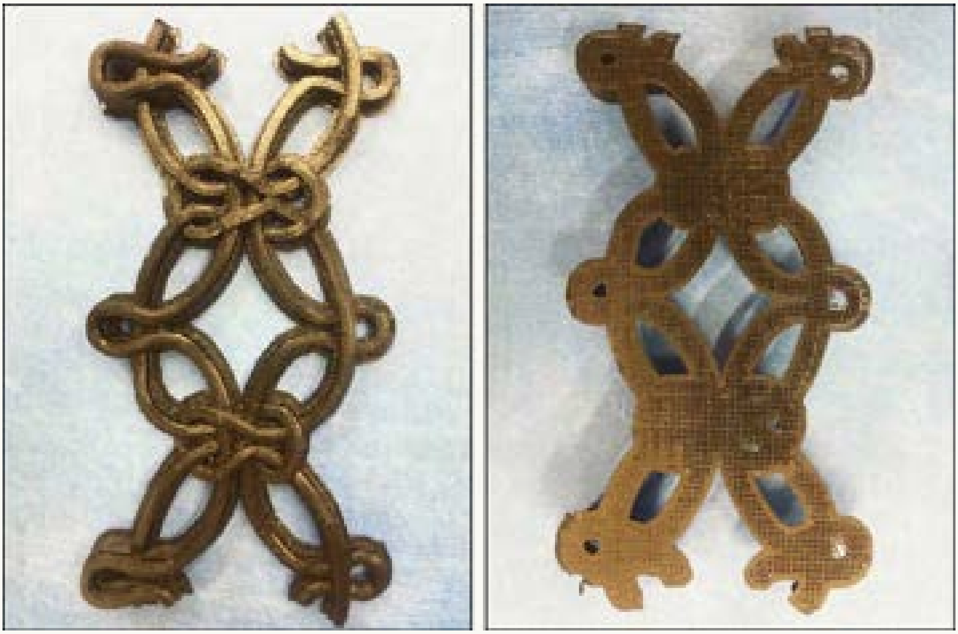

Figure 12. A complete high-resolution print of a section of flexible knots with full support.

rough surface. Two factors contributed to the printing failures: the machine and the setting of the support when generating a g-code file (i.e., tool path coordinates and material parameters) to slice the model. The same 3D model was printed on a different machine. While the result improved areas of cracked surface still occurred (Figure 11).

This output implied that the machine might be influencing the printing process. Next, the slicing/printing parameters were set to generate full, strong support material. A new print was output, but the dense support material was difficult to remove (Figure 12). It seemed that the setting of slicing/printing parameters was perhaps the key. The support material had to be distributed throughout and strong, but also needed to be relatively easy to remove. This approach was used in the next stage of experimentation, the modelling and printing of multi-sectional loose knots (Figure 13).

5. New interdisciplinary craft with 3D powder printing

The Material Matters Research Centre has employed powder printing technology for mould making for use in the metal foundry, glass casting,

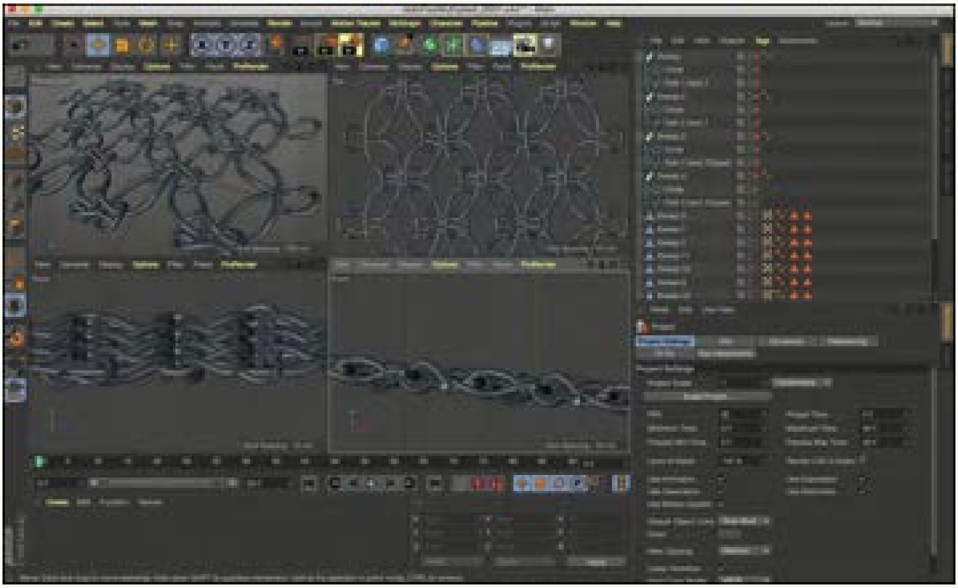

Figure 13. CAD model of multi-sectional knots.

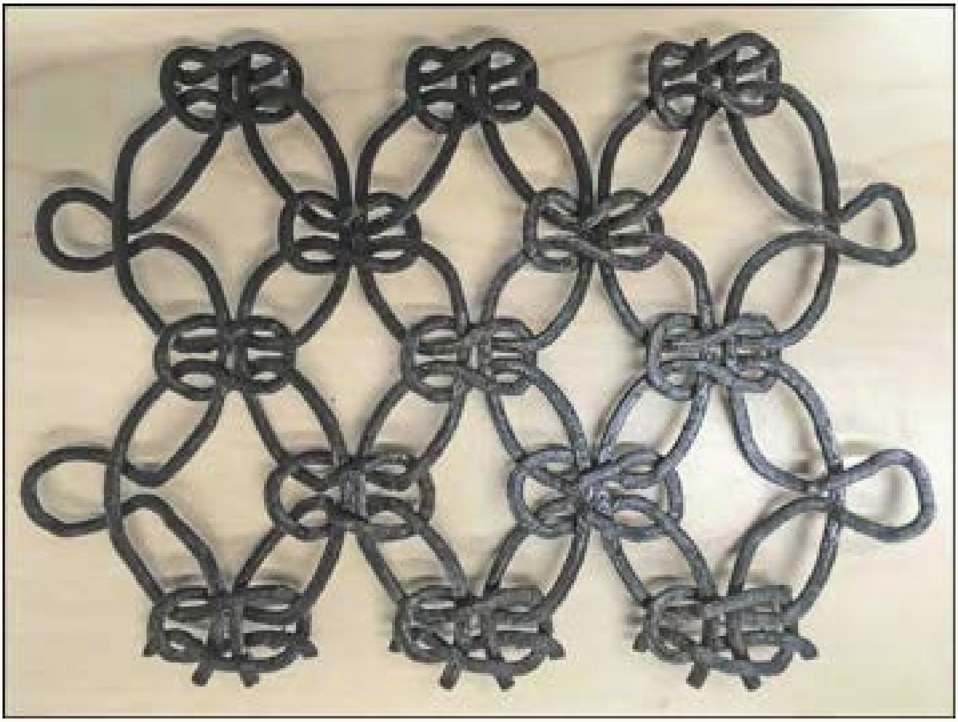

Figure 14. Print of three sections of loose knots.

and slip-casting in previous projects (Oussoren, Robbins, & Doyle, 2015) (Figure 15). While these material techniques seemed far removed from her knot practice, Nimkulrat was interested in learning and applying this method to her work. After accumulating CAD modelling and 3D printing skills, she saw this 3D printing method as a new opportunity for giving her coffee cup function. During her first degree in Industrial Design 20 years ago, Nimkulrat learnt mould making for prototyping (a process where a "pattern" is cast into reusable moulds for reproduction) and traditional ceramics. She therefore understood the general principles of mould making for ceramic slip-casting of multiple parts. Still, not being experts in ceramic slip-casting, Nimkulrat and Oussoren sought advice from Julie York, Associate Professor of Ceramics. Based on advice received they created a CAD model mould for slip-casting a porcelain cup. The mould took into consideration shrinkage and the removal process of the finished cast piece. Figure 16 shows the steps of making a CAD model of the cup mould. A positive form of the cup was made based on the 3D model of the knotted cup used earlier for 3D printing with PLA filament. The knot pattern was repurposed and used as a relief surface detail. A one-inch-thick mould was designed around the cup.

This form was then 3D printed on a Zcorp 310+ binder deposition powder printer, using a custom in-house powder and unique binder reci-

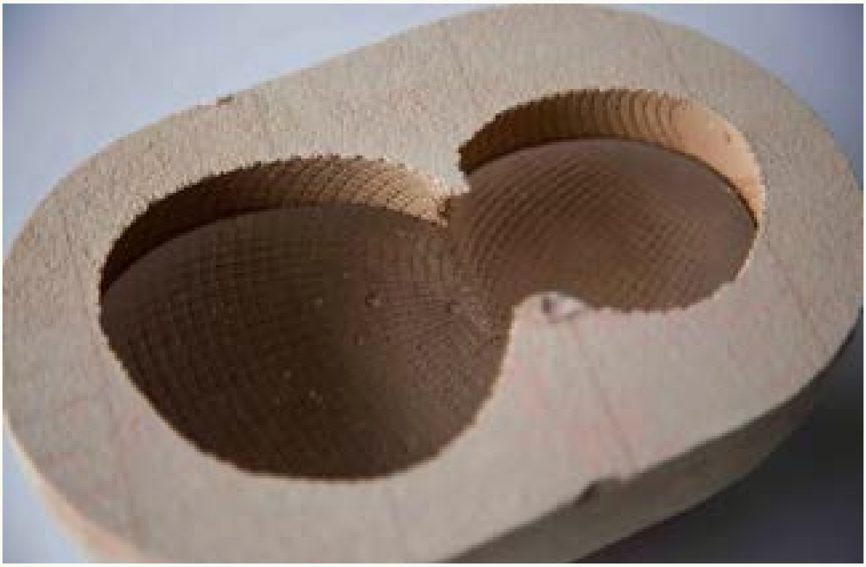

Figure 15. Cast glass in 3D printed mould.

Figure 16. Process of making the CAD model of the cup mould.

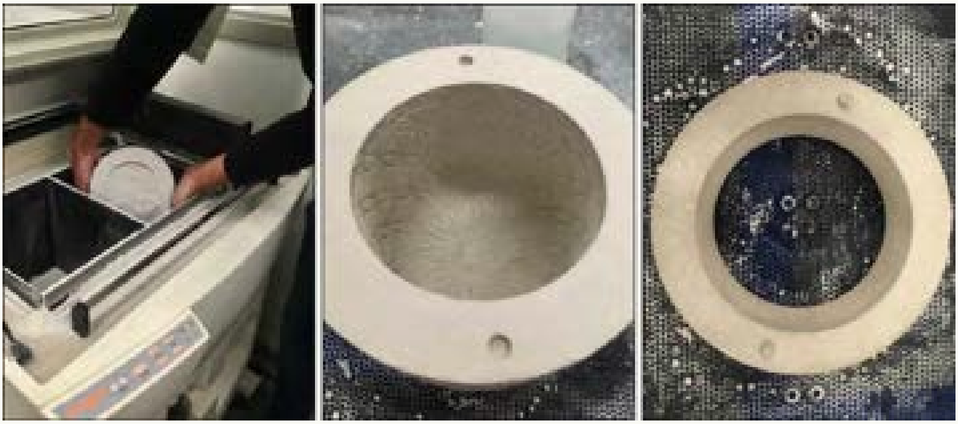

Figure 17. The printed cup mould (bottom piece) is removed from the printer; each piece is sprayed with water and leave to get dry.

Figure 18. Slip casting porcelain using the 3D printed mould.

pes (Oussoren et al., 2015). Upon removal of the mould from the printer, it was sprayed with water to further set the gypsum-based powder substrate increasing its plasticity when dry (Figure 17). The dry mould was used for slip-casting porcelain (Figure 18). As the properties of the material of the digitally-produced mould differed from the plaster commonly used for slip-casting, using it for slip-casting porcelain could not follow the usual principle. For example, the cast pieces need a longer time to set due to the material's higher density.

6. Collaborative making inspiring new practice

The work detailed in Section 5 illustrates design of 3D objects in VR may be translated into glass. For Oussoren, who has worked in a broad range of glass forming methods including glass blowing, kiln, and sand casting (a process where a "pattern" is cast into reusable moulds for reproduction), slumping and fusing, this transition was a natural step (Oussoren et al., 2015). As an affiliated researcher at the research centre, Oussoren has explored, developed, and refined a range of digital fabrication technologies related to ceramics and glass, in collaboration with industry partners. As a sessional instructor at the University he has also mentored classes through processes of design for digital fabrication in a range of materials. His work in collaboration with Nimkulrat, during her residency at the University, utilizing design in VR to generate complex knotted forms for 3D printing afforded new opportunities pertaining to glass design and 3D printing. Oussoren took on a new project that applied the same processes: drawing in VR, developing a mould in CAD, 3D printing in plaster, and then, this time, casting in glass. This direct design from VR to cast glass object described in detail below illustrates new opportunities for form development in craft materials.

The starting point for the work was the ability to capture gesture in VR. Using a drawing program called Gravity Brush, form was generated in a virtual three-dimensional space using VR controllers (Figure 19). This captured gesture was output to Cinema 4D, and used as a positive to generate a mould form. This mould form was then 3D printed in a plaster material suitable for glass casting (Figure 20). After 3D printing, the mould was post-processed using a mould release on the working surfaces of the mould – specifically formulated for use with glass, and dried thoroughly (Figure 21). After drying, the mould was filled with raw material (crushed glass) then fired to full melt temperatures in a digitally-con-

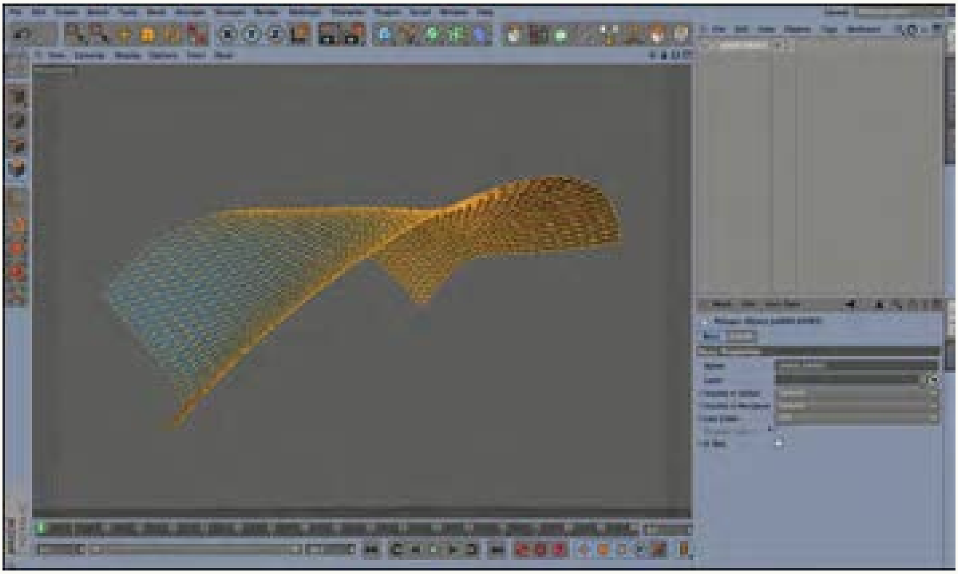

Figure 19. Gestural form captured in Virtual Reality using drawing program Gravity Brush.

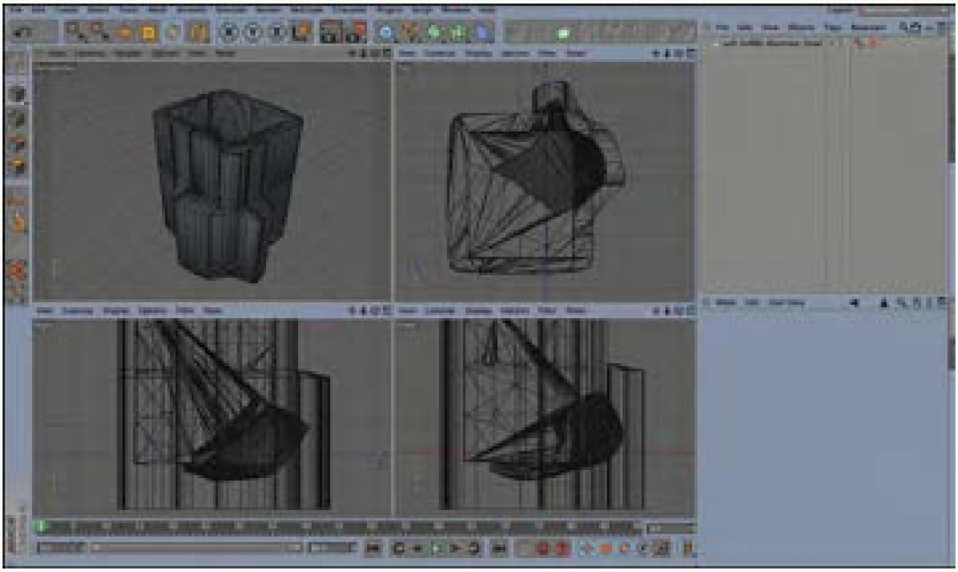

Figure 20. CAD design for mould based on VR form.

Figure 21. 3D printed moulds for glass casting, pre-firing.

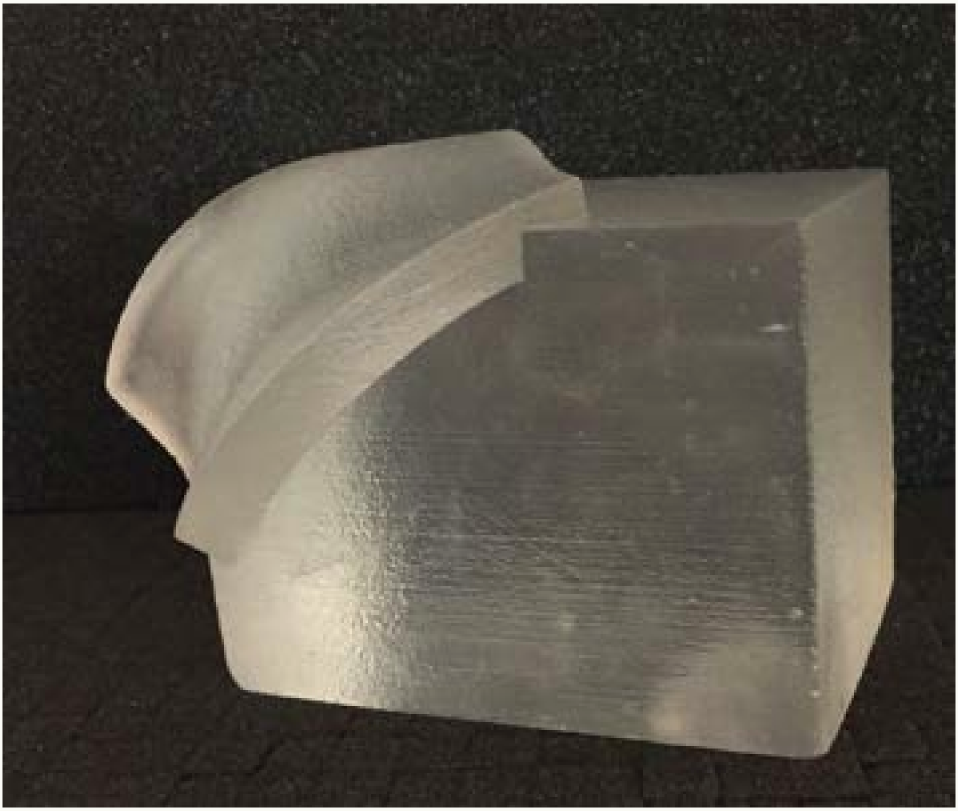

Figure 22. Cast glass from 3D printed mould, based on VR form.

trolled kiln. In this state, the fluid glass then flows to full fuse and fills the pattern void of the mould. This workflow of VR to glass object presents many new opportunities for generating novel forms and surfaces which have previously been difficult or impossible using traditional glass casting and blow-moulding methods. The timeframe for a kiln-casting project is also greatly reduced, as there is no need to make an original positive form to be wasted as required in the age-old process of lost-wax casting method (Figure 22).

The authors' work at the University has explored how traditional material production processes found in ceramics and glass can emulate the freedom of complexity found in computer-aided-design. Integrating 3D printing processes with craft methods enables complex geometries, repeatability, and scalability in the production of traditional analogue materials (Oussoren et al., 2015). A natural question related to digital design and output is how might the digitally-mediated object relate back to the makers hand? In a prescriptive digital design space (Solidworks, Rhino, etc.) form and surface are often dictated by the parameters established by the software. Using VR as a design space may bring our CAD space closer to the nuanced complexity of hand making. In addition to expanding on the expressive potential of CAD, models may be developed in VR in a more intuitive way than other CAD avenues.

7. Emerging pedagogy related to design

The sections above detail a series of research creation activities through collaborative practice, iteration and reflection incorporating emergent craft sensibilities of 3D printing and Virtual Reality technology taking place at Emily Carr University of Art + Design's research labs. These clustered facilities occupy a unique position within the University. They serve as both a compliment and a service to the regular curriculum. They also act to support a rich studio culture at the intersection of research creation, cultural enterprise, and industry. The University's Research Centres employ research assistants (RA) predominantly from the undergraduate and increasingly graduate Design programs within the University. In the curricular context, students are introduced to a diverse range of research methods including, Research through Design (RtD) (Frayling, 1993; Zimmerman, Stolterman, & Forlizzi, 2010), Co-Creative ethnographic practices (Mattelmäki, 2006; Sanders, 2005) and our own faculty approaches to research creation development that make use of sites for provocation and riposte (Day Fraser & Doyle, 2015). The Material Matters Research Centre and the research activities it supports acts to augment this pedagogy. As noted in Section 3 above the approaches taken by expert researchers and the work they produce serves to inspire students working in close proximity as RA's on different projects. It seeds student desires to push their own material practice and design expectations.

The recent successes of modeling in VR lead Nimkulrat and Oussoren to reflect and question – "How has CAD been introduced to teaching students?" In general, CAD training present in the classroom is a linear process, gradual and incremental skills development supports conventional Design for Manufacture and applied skills development. Coursework follows the typical generative arc of design creation, tackling the fuzzy front end of ideation, through to iteration, prototyping, and design concept development. Incremental learning and progressive skills development of the classroom, in this case, is an approach that may limit craft in the context of VR enabled modeling and form generation. The perceived sensorial immersion and embodiment of a modeling workflow in the VR modeling space stands apart from the sequential assembly processes of modelling in CAD through conventional interface. Editable gestural form-making serves up a disruption to conventional design workflows in 3D, and latterly pulls on course delivery.

Form generation in VR and digital fabrication are influencing our semantic approach to meaning making and aesthetics. The gestural interface and immersive environment of the VIVE VR technology and CAD software enable a sustained *naïve expertise* for the practitioner (Wakkary et al., 2016), a creative approach to complex form and unknown spatial geometries akin to a craft approach that lowers the barrier for uptake and understanding. Herein the tensions of crafts' "Certainty and Risk" (Pye, 1968) are mediated by the immediacy of immersive form generation and time reversal. The immersive interface of VR matches an immediacy of material sensibilities in the freely complex digital environment that closely emulates the concerns of the artisan's proximity to raw material.

The research methods used for this particular study of 3D VR modeling are rooted in a history of material practice and research creation activities taking place in our labs via a variety of material explorations in additive manufacturing, direct 3D printing of glass and iterative tooling for foundry. These integrated activities are readily exploiting the aesthetic, formal qualities that are unique to these legacy techniques through the lens of digital modeling to material fabrication processes (Robbins, Doyle, & Day Fraser, 2014). Complimentary research creation activities as described in the previous sections of this paper and concurrent design-led industry and academic partnerships at the labs are providing a means for the development of a unique curriculum, embedding craft sensibilities and concerns into a linear assembly, acting as a discrete site for knowledge transfer and mobilization. This host site supports the push of invention, skills development, and knowledge acquisition for students and University's stakeholders alike.

8. Discussion and conclusion

This emerging practice is inherently collaborative, acting as a catalyst for established disciplines within the arts to collide and interact. Outcomes of this study include mapping new workflows within digital/analogue material practice (Figure 23), and reflection on how the materials and methods used in digital fabrication have the potential to expand and illustrate the meanings in the things that are produced. Throughout this collaborative practice, reflection has been made on each iteration of digitally-fabricated objects and ways in which the analogue and the digi-

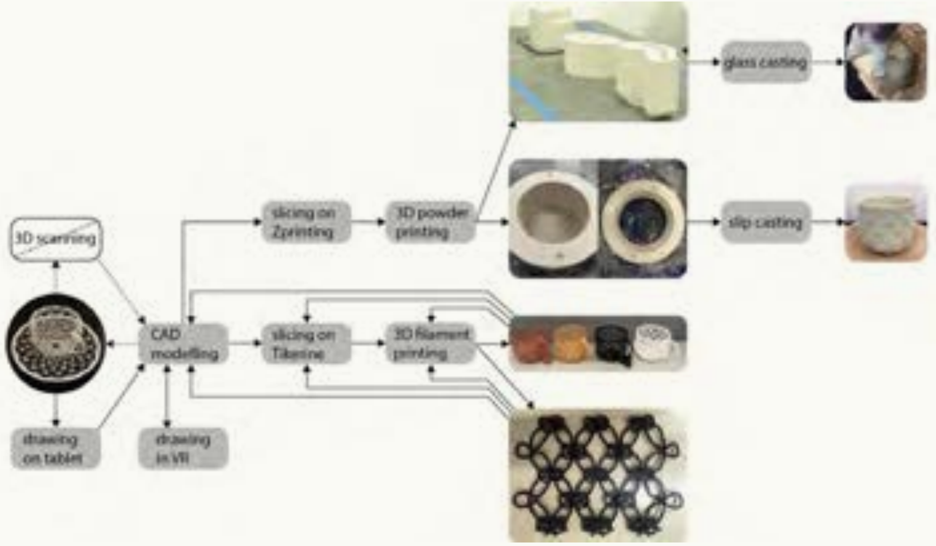

Figure 23. Mapping of the transformation of materiality, from the physical (hand-crafted object) to the digital and back to the physical (digitally-fabricated objects) again, and also from the digital (drawings) to the physical (digitally-fabricated to hand-crafted objects).

tal craft practitioners work together. Through reflection on action, the practitioners make explicit the implicit knowing, turning knowing-in-action into knowledge-in-action (Schön, 1983, p. 25). As Scrivener and Zheng (2012) point out, knowledge-in-action is the practitioner's reflection on the understanding that has been implicit in his or her action – understanding that the practitioner "surfaces, criticizes, restructures, and embodies in further action." Such understanding is evident in the collaborative practice presented in this paper.

The practice exemplified in this paper reveals ways in which digital technology can be use to transfer hand making skill and knowledge into new production contexts. A similarity between working with the analogue and working with the digital that the study has found is the unpredictability of the process. In analogue practice, the exact process cannot be known until the craft practitioner manipulates the material. Likewise, in the manipulation of digital tools, the practitioner cannot predict if the material will take a form similar to the CAD model. Accidents and failures as part of the "craftsmanship of risk" (Pye, 1968) are present in both the analogue and the digital. Materials and tools, of the craft and the digital both, often "resists the maker's intentions and thus actively shape them, revealing new action pathways while closing others (Glăveanu, 2014, p. 55). This is when reflection-on-action becomes helpful; the maker is taken out of the routine of making when contemplating problems in the making that requires a new course of action. Working through iterations opens up the process for the practitioner. It affords skill accumulation, and, when a skill becomes embodied, enables self-consciousness engagement with the process to fade away (Nimkulrat, Niedderer, & Evans, 2016, p. 7). This study, speaks to this process. It reveals an alternative way of learning CAD and 3D modeling, through collaborative, interdisciplinary practice.

This work provided opportunity for reflection on a mixed digital/analogue practice, and what collaboration means in these spaces. To a certain extent a material practice is by necessity collaborative, as it requires knowledge of a range of processes, tools, and materials. This mix of tacit and explicit knowledge is generally gained directly from experts and practitioners in the field. While CAD work has been theorized as working in a "digital material" or "digital craft" (Shillito, 2013), the ways that a digital practice and an analogue material practice engage with knowledge are quite different. A design practice that is heavy in CAD will utilize explicit knowledge and may be collaborative on digital social platforms. A design practice involving material research and development will, through necessity, engage with tacit first hand knowledge. Our plans moving forward are to continue to explore this – asking what are the emergent workflows of collaboration in this mixed digital/analogue practice.

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