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# Thinking Through Knitting: Hand Knit making for rapid architectural prototyping

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This paper demonstrates the value of hand knit process in architectural prototyping. Knit is a highly specifiable, additive manufacturing process. Knit architectures rely on knit fabric properties to generate form which requires prototyping to assess material behaviour; this is developed in conjunction with computational design approaches. Hand knit can be a successful alternative in prototyping, combining simplicity of production with additional craft knowledge gained through the experience of manipulating materials directly. Four parameters were investigated at two scales of materials, resulting in a lexicon of knitted forms. The outcomes demonstrated self-supporting 3-D forms utilising the inherent curvature of knitted fabrics and integral shaping techniques. The importance of hand process in the investigation was key, allowing simultaneous evaluation of materials and production methods but more importantly extending the cognitive dimension of design development by restoring the intimate relationship between maker and materials experienced through craft process.

***Keywords: hand process; knit thinking; rapid prototyping; knit architecture.***

## 1 Introduction

In the last 10 years, new material systems applying textile processes have evolved from speculative research into contemporary architecture (Sabin et al 2018). Advanced Knitting technologies enable the design and manufacture of high-performance fabrics, and the field of knitted architecture is gaining huge momentum as designers exploit the programming capabilities of knit at an architectural scale (Alhquist 2016; Gengnagel et al 2016).

As new concepts develop, rapid prototyping techniques are critical to test ideas and work across disciplinary boundaries (Stacey, 2013). In post-digital design practice, rapid prototyping is synonymous with 3D printing, however this process requires a digital interface between designer and material (Lipson 2012, McCullough 1996). As architecture begins to incorporate lightweight and flexible textile components, it is essential that prototyping techniques diversify meet the needs of designers working with these specialised material systems.

Knit architectures benefit from computational design approaches, but material prototypes are required to inform fabric performance and form finding and this usually relies on digital knit technologies. Complex form can also be produced using hand process, and whilst this is not conventionally synonymous with high-speed production, for small scale rapid prototyping, hand knit can be a powerful design tool. A tool that incorporates fabrication with additional knowledge gained through the experience of manipulating materials directly.

This research paper examines how handknit can act as a rapid prototyping technique for knit architecture, evaluating the impact of hand knit prototyping on material selection and the development of fabric structure and complex form. In addition, the paper assesses how hand knit prototyping can inform scale, and the paper evaluates how knowledge can translate into production control for digital knit technologies. As such the overall aim of this research is to examine how knit thinking can inform architectural prototyping using handknit production.

# 2 Background

## 2.1 Knit as 3D manufacturing

Knit could be described as one of the earliest forms of additive, three-dimensional manufacture. Nålbindning, a loop construction process, the forerunner of contemporary knit, has been used to produce seamless garments since the third century (CE), with early examples originating in Egypt (Burnham 1972). By the 16th century, knit, recognisable as the technique used today, was used widely in Europe for caps and stockings and eventually full jumpers, again produced as complete three-dimensional garments (Rutt 1989). Despite the first knitting machines dating back to 1589, effective three-dimensional machine knit wasn't available until the 1990's with the development by knitting machine manufacturers of Shima Seiki Wholegarment© technology and Stoll Knit and Wear© technology. This machine development was made possible by improvements to machine production control and improved CNC interfaces. As their names suggest, these developments were aimed at garment production, however they enabled the use of knit as a viable industrial three-dimensional production process, and their use has widened to diverse industries and scales from medical implants to architecture. Knit architecture is a particularly interesting field in relation to prototyping because the development of large scale knitted installations and pavilions is closely aligned to research in computation modelling and simulation of knitted fabrics and forms.

Despite improvements to knitting machine programming interfaces, the production of three-dimensional machine knit is complex and requires an iterative production sequence to refine programmes for successful fabric generation. This is particularly apparent at early, investigative stages of design development where material choices can impact fabric outcomes. Hand prototyping can solve some technical production problems prior to complex machine programming and for small, exploratory pieces hand knit is well suited as a production process.

## 2.2 Hand knit for rapid prototyping

The major advantage of hand knit prototyping is that the process is responsive. An expert knitter uses their understanding of materials, fabric structure and production control for exploratory, three-dimensional form finding. During knitting, material properties and fabric structure can be modified quickly, and their effect on fabric properties assessed concurrently throughout production. De- and re-knitting allows different production options to be evaluated in real time. This intimate relationship between design and product is unique in hand process and removes the CAD interface necessary in other rapid prototyping methods.

The use of hand knit however offers more than the opportunity to control and change technical parameters quickly. Craft theory identifies the importance of the relationship between the maker and the material, and how knowledge is generated through a thinking process closely aligned to the process of making itself (Adamson 2007). In hand knit this cognitive dimension encourages creative making in the space between haptic sensation and thought and extends the concepts of design thinking (Cross 2011, Dorst 2003, Walker 2006) to the process specific *knit thinking* (Scott and Gaston). Knit thinking-based research uses exploratory abductive reasoning, to combine tacit craft knowledge and explicit technical knowledge reflectively and intuitively (Dudley and Mealing, 2000) in the craft-based domain of materials, process and skill. Generative form-finding through iterative experimentation produced three-dimensional knitted maquettes.

# 3 Materials and Methods

This paper examines four parameters of materials, fabric structure, production control and scale (figure 1) in the application of hand knit as a rapid prototyping tool for architecture. As such the aim of this research is to examines how knit thinking can inform architectural prototyping using handknit production.

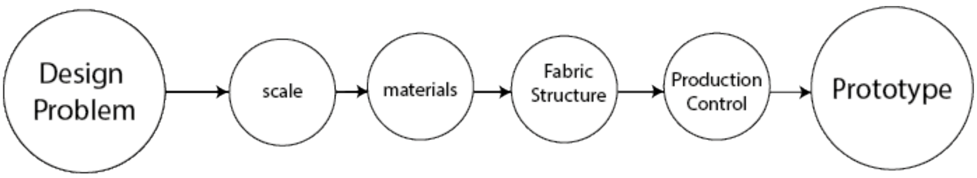


*Figure 1: Linear Prototyping with specification of key parameters.*

Researchers were focused on challenging a range of assumptions related to 3D knitting for architecture encountered through previous work using digital 3D knit technologies (Underwood 2009). The research addresses how handknit prototyping could improve the design of 3D knit preforms suitable for knitted architecture. In particular, the placement and orientation of branching structures within 3D knit preforms is examined. As such the research questions ask:

- How can handknit prototyping improve the placement and orientation of branching structures within 3D knit preforms?
- How can handknit prototyping inform the design of 3D knit preforms for knitted architecture

The research process has been undertaken in two stages; firstly hand knit prototypes incorporating the 3D knit preforms have been developed at a small scale (10-20cm) to explore the placement and orientation of branching structures. Secondly a 1.5m prototype was produced applying the knit preforms at an architectural scale. Central to the investigation was a re-evaluation of the behaviour of knitted fabric in relation to stitch structure and material use. Specifically, the role of the stitch as a tool for manipulating fabric structure and its effect on three-dimensional form. Whereas the programming interfaces for CNC knit technology separate fabric structure from information about materials (yarn type is not specified with a knit programme), this research combines stitch configuration and material properties for generative form finding. This is significant for architectural prototyping because it can enable complex form to be expressed at a material level within architectural forms.

## 3.1 Materials

The fundamental requirements of a yarn suitable for knit are length, strength and flexibility. The properties of the constituent fibres provide the characteristics of the yarn, which is further manipulated by spinning parameters. In this research yarn properties are transformed with scale. Small scale prototypes are composed of a commercially available cotton tape yarn. Yarn properties directly inform the knit performance.  Fibres in the cotton tape have been spun into a high twist single yarn enhancing rigidity and tensile strength. In addition, three ends of the cotton singles have been knitted into a tape yarn with a round profile which produces a yarn that creates clear stitch definition with good fabric rigidity. The knitted tape construction provides some inherent stretch in the yarn which is favourable for loop construction processes. For the large-scale prototype an unconventional ‘yarn’ with a large diameter (1.5cm) was selected in an attempt to translate the scale via materials enabling the stitch pattern to remain constant.

## 3.2 Fabric structure

Weft knit is also an additive construction process, where knitted loops are formed sequentially in horizontal courses by drawing a yarn through the loops of the previous course of knitting (Spencer, 1989). Knitted fabrics can be produced two dimensionally in a plane, where the stiches are formed in opposing directions in alternate courses or in three dimensions, where the stitches are formed spirally in the round (fig 2). The shape of two- and three-dimensional knitted fabrics can be further manipulated by increasing and decreasing the number of stitches in use at any time. In this research, knitted fabrics have been produced integrally as three-dimensional preforms based on a plain knit structure with tubular and branching configurations.

*Figure 2: Knitted Fabric Structures: left to right rib and plain (stitches formed in opposing directions on alternate courses), partial knit (increasing and decreasing stitches), tubular (stitches formed spirally in the round).*

### 3.3 Production control

Loop length is the fundamental unit for fabric production control and in hand knit is determined by needle diameter, specified in millimetres. For this research manipulation of loop length was be achieved through varying the yarn tension and needle size. A small loop length will produce a tighter more rigid fabric which will allow three dimensional knitted fabrics to maintain their form.

### 3.4 Scale

The ability to generate self-supporting fabrics relies on the structural integrity of the material The integrity of form is also influenced by the scale of the knitted fabric in that a small three-dimensional fabric may hold its form but if the fabric dimensions are scaled up whilst using the same materials and production control, the form of the three-dimensional fabric may no longer be self-supporting.

To investigate the impact of scale and production control fabrics were produced at loop lengths smaller than manufacturer's recommendations for example the R0.4Nm 100% cotton tape yarn was knitted on 5mm needles (manufacturer's recommendation 6-7mm) to produce small, semi-rigid, self-supporting forms.

## 4 Results and Reflections.

### 4.1 Prototyping 1: 3D Knit Preforms

The first series of prototypes document the production of 3D knit preforms that integrate multiple branching structures. The forms achieve high levels of structural integrity achieved by adapting stitch configuration during the hand knit process. The prototypes were knitted in cotton tape yarn with production control maintained through control of loop length and needle size. This has produced a shape lexicon for 3D knit preforms, focused on the placement and orientation of branching structures within tubular prototypes.

In each example multiple tubes are positioned in relation to a principal tube using the inherent curvature of a knitted fabric to enable form generation. The pattern notation included within table 1 is a conventional hand knit notation, this is recorded as the fabrics are produced.

| Prototype | Knit model | Description | Pattern notation |
|---|---|---|---|
| Fan<br><br>5mm needles<br>Cotton 0.4 Nm<br>Stitch length 45mm<br>Stitch density $1.1/cm^2$ |  | Branching structure multiple tubes divided along one plane. | Round 1-8 k<br>Round 9 (inc1, k1) x12 [36]<br>Round 10 and subsequent even rounds k<br>Round 11 (inc1, k3, inc1, k1) x6 [48]<br>Round 13 (inc1, k5, inc1, k1) x6 [60]<br>Round 15 (inc1, k7, inc1, k1) x6 [72]<br>*Divide sts 1-21 equally over 3 needles.<br>Round 17-27 k<br>Cast off sts 1-21<br>Repeat from * for sts 25-36 & 60-72 and sts 37-59 |

| | | | |
|---|---|---|---|
| Tripod<br><br>5mm needles<br>Cotton 0.4 Nm<br>Stitch length<br>45mm<br>Stitch density<br>1.1/cm$^2$ |  | Branching structure, multiple tubes branching from centre | Round 1-8 k[21]<br>Round 9 (inc1) x21[42]<br>Round 10-12 k<br>Round 13 (inc1, k1) x21 [63]<br>Round 14-16 k<br>*Divide sts 1-21 equally over 3 needles holders.<br>Round 17-27 k<br>Cast off sts 1-21 |
| Capillary<br><br>5mm needles<br>Cotton 0.4 Nm<br>Stitch length<br>45mm<br>Stitch density<br>1.1/cm$^2$ |  | Branching structure; multiple tubes branching from centre as node. | Round 1-8 k[21]<br>Round 9 (inc1) x21[42]<br>Round 10-12 k<br>Round 13 (inc1, k1) x21 [63]<br>Round 14-16 k<br>*Divide first 9 sts equally over 3 needles holders.<br>Round 17-27 k<br>Cast off 9 sts<br>Repeat from * in groups of 9 sts |
| Jake<br><br>5mm needles<br>Cotton 0.4 Nm<br>Stitch length<br>45mm<br>Stitch density<br>1.1/cm$^2$ |  | Branching structure, central node with 3 branches at top and 3 branches at bottom | *Round 1-12 K [8]<br>Cut thread and place sts. on holder<br>repeat from * x 2<br>Move all sts. From holders back to needles in the following order<br>Tube1 sts.1-4, tube2 sts.1-4, tube3 sts.1-8, tube2 sts.5-8, tube1 sts.5-8<br>Round 1 K[24]<br>Round 2 k3, sl1, k1, psso, k2, k2tog, k6,sl1, k1, psso, k2, k2to, k3 [20]<br>Round 3 k<br>Round 4 k3, sl1, k1, psso, k2tog, k6,sl1, k1, psso, k2to, k3 [16]<br>Round 5 k<br>Round 6 k4, m1, k8, m1, k4 [18]<br>Round 7 k<br>Round 8 k3, place sts. 12 sts. On holder, k3<br>Round9-24 k<br>Pick up sts.4-6 and 13-15<br>Round 1-25 k<br>Pick up sts.7-12<br>Round 1-15 k |
| Jake x 3<br><br>5mm needles<br>Cotton 0.4 Nm<br>Stitch length<br>45mm<br>Stitch density<br>1.1/cm$^2$ |  | Three Jake forms linked to form free standing structure. | |
| Lizard<br><br>5mm needles<br>Cotton 0.4 Nm<br>Stitch length<br>45mm<br>Stitch density<br>1.1/cm$^2$ |  | Branching structure, central tube with branches left and right | Round1-6 K<br>Round 7 inc.1, inc.1, inc.1, inc.1[8]<br>Round 8 *move st.1 to st. holder A, inc.1, inc.1, move 2 sts. to st. holder B, inc.1, inc.1, move 1 st to st. holder A<br>Round 9 Repeat from *<br>Round 10 K<br>Round 11-13 repeat last 3 rounds using st. holders C&D<br>Round 14-20 k<br>Pick up sts from holder A<br>Round 1-10 K<br>Pick up sts from holder B<br>Round 1-10 K<br>Pick up sts from holder C<br>Round 1-10 K<br>Pick up sts from holder D<br>Round 1-10 K |

*Table 1: Knit prototypes*

## 4.2 Prototyping 2: Experimental Knit Architecture

Analysis of the 3D knit preforms identified how the position of branching components can be altered through the knitting pattern, integrating the complex organisation of the branches into the structure of the preform. This led to the design of a large-scale prototype to investigate what impact materials, fabric structure and production control have at a scale. This large-scale prototype was knitted from British Cheviot wool roving (diameter 1.5cm, untwisted) based on Jake (table 1); a node with three branches at the base and three branches at the top. The experimental architecture was assembled from 4 knitted preforms. The prototype was assembled using grafting to retain material performance after assembly (Scott, Gaston, Agraviador, 2021). Whilst the small scale preforms are self-supporting, the experimental architecture integrated inflatable beams into construction to enable the work to stand up.

*Figure 3: Experimental Knitted Architecture*

*Figure 4: Organisation of 3D knit Preforms.*

*Figure 5: Curvature expressed through material and structure.*

*Figure 6: Detail of Node with Branches.*

## 4.3 Analysis and Evaluation

At a small scale knitted preforms demonstrate how changes to a knitting pattern can enable careful placement and orientation of branches within knitted preforms. Whilst the knitting notation appears straightforward, the way that the stitches are manipulated within the preform enables each prototype to generate unique branching structures. By applying this knowledge at a large scale, knitted preforms created using the same knit structure (pattern) were transformed into an experimental architecture. Scale was controlled by increasing the diameter of the constituent yarns rather than increasing the number of stitches knitting so the knitting notation is constant at the two scales. Here the impact of materials can been clearly seen; the large scale prototype requires the support of inflated beams to hold its form, wheras the small scale preforms are self-supporting. Production control at both scales was manually determined through the hand knit process.

Hand knit offers a rapid process to transform 3D concepts into knit knowledge suitable for transfer into the programming language necessary for CNC knit technologies. This research demonstrates how this knowledge can be applied at two scales, to translate findings from hand knit to industrial knitting a different strategy for scale up is required due to machine stitch length specifications. Despite this, the learning achieved from undertaking handknit prototyping can be applied within a programming interface to reduce programming time for designers.

## 5 Conclusions: Knit Thinking and Thinking Through Knitting

Findings of this research demonstrate how much we can learn by returning to traditional forms of making that privilege the material and the hand. The production of a successful knitted three-dimensional form is a system reliant on the interaction of materials, fabric structure determined by stitch configuration, production control and fabric scale. These parameters can be specified for digital knit technologies in a similar way to other forms of rapid prototyping, however hand knit processes enable direct engagement through the making process. Ingold describes this *thinking through making* as an alternative form of knowledge generation that lies in the process of physically experiencing the material rather than imposing form on it (Ingold 2013). This produces alternative and expanded knowledge obtained through the experience of physically *thinking through knitting* (figure 6) as opposed to the specification process that underpins digital production (figure 1).

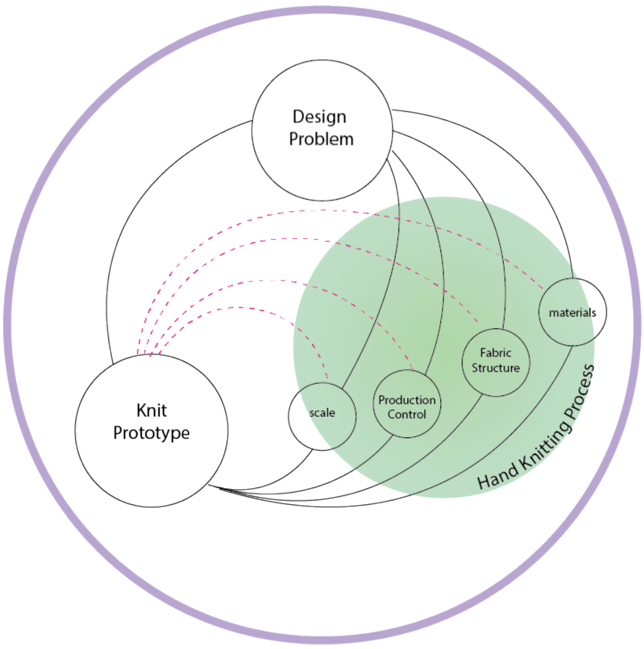


*Figure 7: The Thinking Through Knitting Process*

Key observations in this research highlight how the *thinking through knitting* process enables hand-knit architectural prototyping to extend the shape lexicon of knitting in architecture. This is due to the continual feedback through physical making process and the ability to adapt structure, pattern and control throughout the hand knit process (figure 7). Through a re-evaluation of the relationship between materials (yarn) and shape (stitch configuration) and scale alongside production control mechanisms the tacit knowledge gained using handknit and freeform production methods repositions making as central to the prototyping process.

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